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THE FRISCO MINE, CHIHUAHUA, MEXICO[1]

G. S. KOCH, JR.

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[1] Part of a doctoral thesis entitled "Geologic Structure of the Frisco mine, Chihuahua, Mexico," submitted to Harvard University in 1955.

ABSTRACT

The Frisco mine is near the city of Parral, in southern Chihuahua, Mexico. It is worked by San Francisco Mines of Mexico, Ltd., and produces daily 1,500 metric tons of ore with a grade of 0.5 gram (0.015 ounce) of gold per metric ton, 150 grams (5 ounces) of silver, 5 percent of lead, 8 percent of zinc, and 0.6 percent of copper.

The ore comes from about 32 fissure veins, which occupy faults of small displacement in a calcareous shale formation of probable Cretaceous age. The veins are arranged in a complex pattern whose description and explanation is the principal aim of the paper. From their attitudes and physical characteristics, the veins can be grouped into four sets of mutually parallel veins, each set parallel to a different imaginary plane. These four sets make up two systems of veins, each composed of two sets of conjugate shears. The two systems are believed to have resulted from two stages of deformation—distinct in orientation of stress [illegible] not necessarily separated by any large amount of time.

The vein matter was probably introduced by a hydrothermal fluid during the second stage of deformation, when the fractures of the second system were formed and those of the first system were reopened. The walls and breccia fragments within the veins were silicified and silicated, with the formation of quartz, diopside, actinolite, epidote, and ilvaite. During the same general epoch, but somewhat later at any one place, the sulfide minerals sphalerite, galena, chalcopyrite, pyrite, and arsenopyrite were deposited—in large part as replacements of altered shale fragments. In most places, the last minerals deposited were quartz, fluorite, and calcite. The mineralogy is like that of skarn deposits and like that of the veins at nearby Santa Barbara, which Lindgren included in his hypothermal class.

INTRODUCTION

Location.—The Frisco mine is at San Francisco del Oro in the Parral mining district near the southern border of the state of Chihuahua, Mexico (Fig. 1). The mine is operated by San Francisco Mines of Mexico, Ltd., which also operates the Clarines mine at nearby Santa Barbara (Fig. 1). The American Smelting and Refining Company operates other mines at Santa Barbara and the La Prieta mine at Parral. The Esmeralda mine near Parral is worked by a subsidiary of the Eagle-Picher Company and various small companies and groups of miners are also active.

The village of San Francisco del Oro is 18 km southwest of the city of Parral (Fig. 1), with which it is connected by a macadam road and a branch line of the National Railways of Mexico. The countryside is one of rugged hills or gently rolling plains. The average annual rainfall is probably between 15 and 20 inches, and the range between 10 and 30 inches.

History and Production.—The first veins in the Parral district were discovered at Santa Barbara about 1560, and initially were worked for free gold (43). The last veins found were those at San Francisco del Oro, sometime in the 1650's, and they have been mined intermittently since then, although only on a small scale until recent years when base metals could be profitably produced. At present the Frisco mine is the largest single mine in the Parral district and produces 1,500 metric tons of ore daily. The grade of the ore averages 0.5 gram (0.015 oz) of gold per metric ton, 150 grams (5 oz) of silver, 5 percent of lead, 8 percent of zinc, and 0.6 percent of copper.

Geological Work.—Geological work at the Frisco mine was begun by J. G. Barry in 1923 and has been continued to the present by several geologists and engineers. No description of the geology has been published except a brief account by Dauth (6). The purpose of the present study was to describe and interpret the geology of a large mine with a particularly interesting pattern of veins. The writer spent two years at the mine and six months in the laboratory at Harvard University.

Geology of the Parral District.—The Parral district lies on the border between the physiographic provinces of the Central Plateau and the Sierra Madre Occidental (14). The best geologic map of northern Mexico is by P. B. King (16), who also compiled the same area of the smaller scale and less detailed, but more accessible, map published by the Geological Society of America (39). The geology of northern Mexico is treated by Garfias and Chapin (10), Hovey (11), Kellum (14), P. B. King (15), and R. E. King (17).

The Central Plateau is a southern continuation of the Basin and Range province of the United States, characterized by isolated mountain ranges that trend northward and are separated by wide basins floored with alluvium. The mountain ranges are composed mainly of folded and faulted sedimentary rocks of Mesozoic age. The geology of the Sierra Madre Occidental is very imperfectly known, but R. E. King's (17) work indicates that it is an area largely of Tertiary volcanic rocks, which are uplifted and much broken by block faulting. Along the western margin of the Sierra Madre Occidental and in a few inliers, greatly deformed Mesozoic rocks underlie the Tertiary volcanics.

Although no description of the geology of the entire Parral district has been published, Waitz (41) and Schmitt (29, 30, 31, 32) have written about areas near the cities of Parral and Santa Barbara. Other useful accounts of nearby areas were written by Weed (42), Ordóñez (25), Smith (35), Spurr (36, vol. 2, p. 669–674), and Wilson and Rocha (44). The following outline of the geology of the district is largely taken from the works of these men, especially Schmitt.

The oldest rocks known in the Parral district are a thick series of folded limestones and shales of probable Cretaceous age. These rocks are covered by a thick series of volcanic rocks of probable Tertiary age. Both "the volcanic and sedimentary rocks are broken by great normal faults that generally strike north-south and have dip slips as great as 450 m" (30) and are cut by a variety of dikes and, at Parral, by a small stock of quartz-monzonite. Some of the veins near the city of Parral follow these normal faults or dikes. On the other hand the veins at San Francisco del Oro and Santa Barbara are older than the volcanic rocks in those areas as they cut the shale alone and are themselves cut by all the younger rocks. The relations of the volcanic rocks in the district are not clear.

From ammonites found near the Palmilla mine (Fig. 1), Burckhardt (3, p. 174) dated the shale as middle Cretaceous (Gault-Vraconnien stage). Unfortunately, the ammonites have not been found in recent years, and, as the

circumstances of the original find are uncertain (3, p. 174), the age assignment is best regarded as tentative.

GEOLOGY OF THE FRISCO MINE

The geology of the area overlying the Frisco mine is represented by Figures 2 and 3. The veins occupy fault fissures of small displacement that cut only shale. Both the shale and veins are cut by rhyolite and diabase dikes and are overlain unconformably by a gravel formation and basalt flows. The shale is folded into an asymmetrical, gently-plunging anticline with gently-dipping limbs. The veins worked by the Frisco mine lie on one limb of the anticline.

Country Rocks

Shale.—The most widespread rock in the Frisco mine area, as well as the country rock for all of the veins, is a thick calcareous shale formation, which has not been traced into the shale at Parral but must be of the same or nearly the same age (probably middle Cretaceous). In Pettijohn's (26, p. 269) usage, the shale might better be called argillite if the name shale were not already well-established locally. No marker beds are recognized within the formation and neither the top nor bottom is known. Neglecting the unlikely possibility that many beds are repeated by folding, the formation is at least 800 m thick, as it persists to the bottom of the North shaft of the Frisco mine.

The shale is blue, grey, or black, and ranges from non-calcareous shale to almost pure limestone, with the greater part calcareous. The distribution of lime is not known but the proportion of calcareous beds varies both laterally and stratigraphically, with poorly-defined zones of limestone visible in some places. Although most of the shale is very fine grained, the calcite in some beds has been recrystallized to grains 5 mm across. Some beds contain up to 1 percent of pyrite. There are a few sand lenses and beds of limestone conglomerate, but none are continuous enough to serve as marker beds. The rock is non-porous, impermeable, hard, and highly indurated. Bedding planes are smooth, and in many places slickensided. The beds range from 1 mm to 25 cm thick, and average 5 cm thick.

Contrary to the behavior of most shales, the shale in the Frisco mine is strong enough to have broken with the formation of extended, continuous vein-fractures with large open spaces. Its strength is attested by the fact that throughout the mine large open stopes up to at least 200 by 60 by 5 m and dipping 60 degrees stand indefinitely without support. Although this strength partly results from silicification adjacent to the veins, most of the workings away from the veins also stand indefinitely without timbering.

The shale is folded into an asymmetrical anticline (Figs. 2 and 3) whose southwest limb dips about 30 degrees west and whose north limb dips about 8 degrees north. The fold axis strikes N 28° W and plunges 12° N; the axial plane strikes N 33° W and dips 75° E. Except for extreme local irregularity on the short limbs of isoclinal drag folds and in faulted zones, the bedding is regular on both limbs of the anticline. In the mine, the regular bedding per-

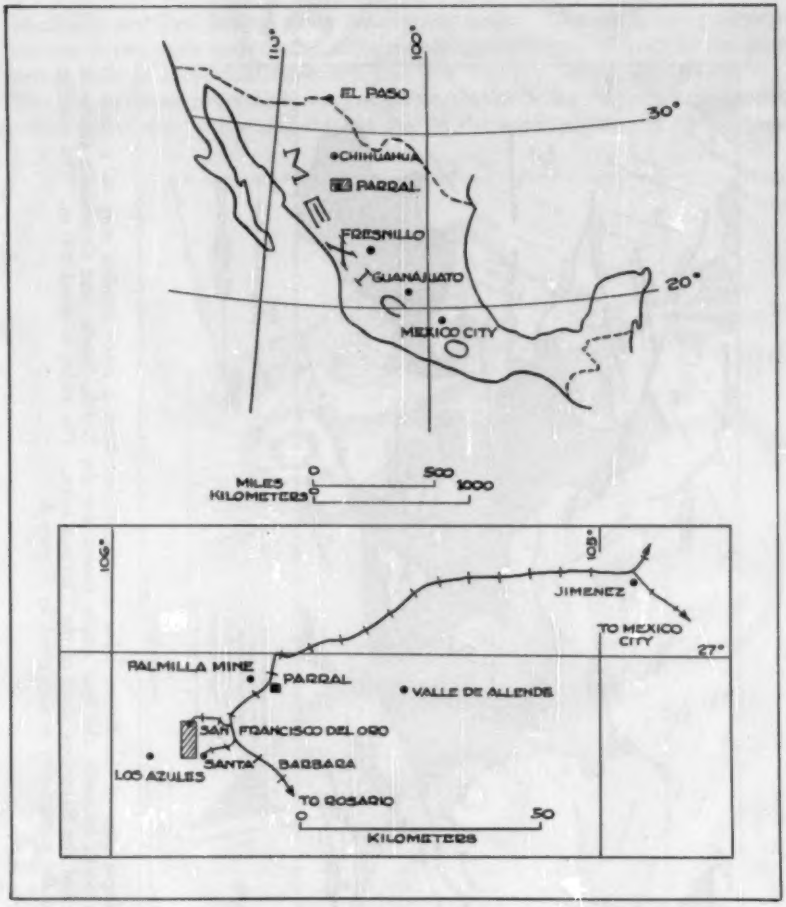


FIG. 1. Index maps showing location of the Parral district, Chihuahua, Mexico. The included rectangle is that of the geologic map, Figure 2.

sists throughout, with the dip ranging from 6 to 12 degrees. Lineation, which is of tiny crenulations and intersections of bedding and cleavage, is strongly oriented in a direction nearly parallel to the fold axis.

Although the major structure of the shale is simple, the detailed structure is complex because the individual shale beds are thrown into complicated drag folds and broken by numerous small faults. Figure 4 shows typical drag folds exposed in a large outcrop whose face is nearly perpendicular to the fold axis of the major anticline. Only part of the outcrop is shown but the rest of the shale in the outcrop is folded in the same way. The shale was first folded

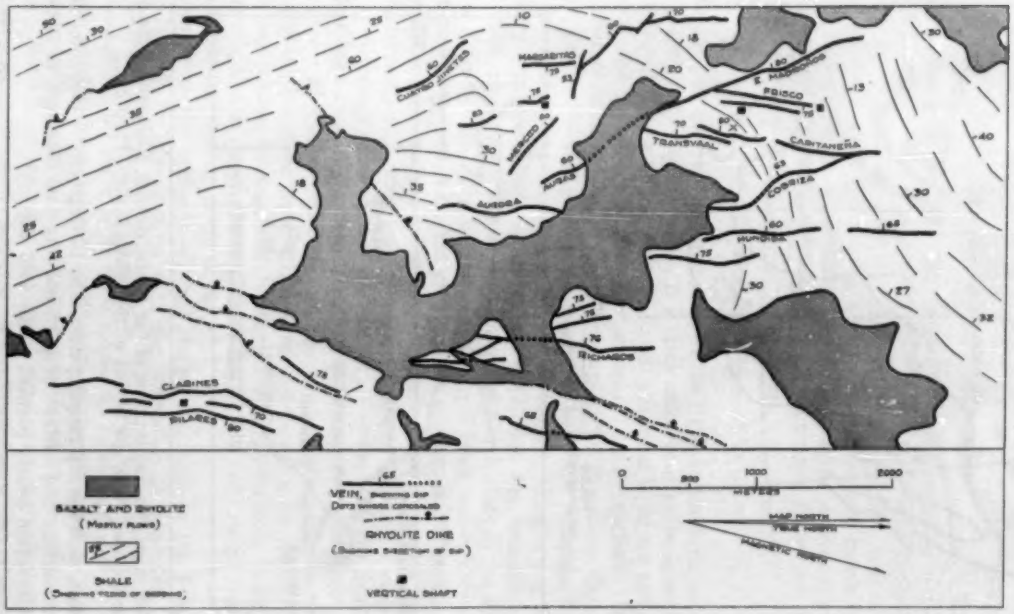


FIG. 2. Geologic map of the Frisco mine area, simplified from a more detailed map on a scale of 1:10,000. From north to south, the four shafts shown are the North, South, and Granadeña shafts of the Frisco mine and the Remedios shaft of the Clarines mine. The relief is about 300 m. The relation of the geology to the topography is suggested by Figure 3.

isoclinally and then faulted along flat-dipping faults. The faults are evidently reverse faults, with each of the slices moved upward with respect to the slice below, just as individual beds slip past one another during flexure folding. The displacement is certainly very small on all the faults except the steep one at the left of the picture and the flat one on the lower right. The maximum

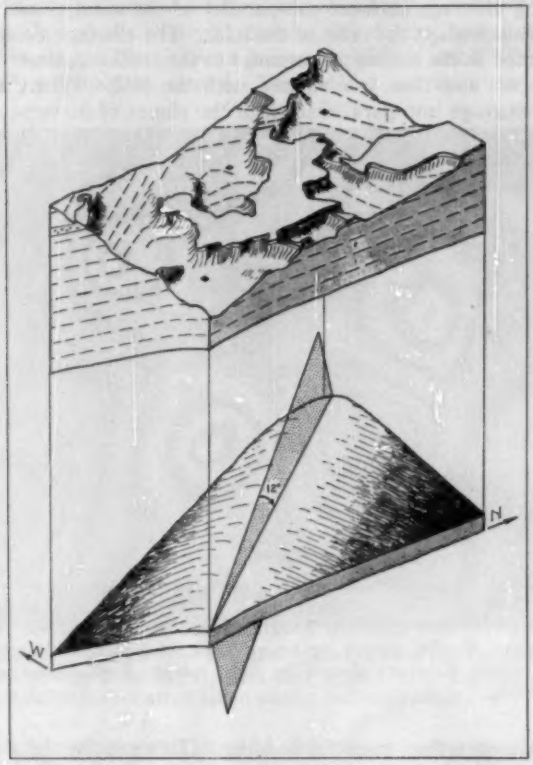


FIG. 3. Block diagram showing the structure of the major anticline. The axial plane is outlined by a stippled pattern. The three shafts shown on the surface by black diamonds are, from north to south, the North and Granadeña shafts of the Frisco mine and the Remedios shaft of the Clarines mine. Vertical exaggeration 15%.

displacement can probably be measured in meters, or at the most in a few tens of meters. Although the drag folds suggest overturning, cross bedding and graded bedding indicate that actually the beds are right side up. The beds on either side of the folded zone are parallel to each other and to the general trend of the bedding at that position in the major anticline.

This outcrop and many more lead one to the conclusion that movement was mainly along bedding planes and along faults oriented parallel to bedding planes, with isoclinal drag folding an early phenomenon caused by slight differences in competency among beds. This view is reenforced by a study of the behavior of single folds, such as that illustrated by Figure 5. Here, the first movement was flexure folding; the later movement shear folding along gently-fanning cleavage surfaces sub-parallel to the axial plane, resulting in thickening of the beds at the crest of the fold. The cleavage evidently formed at an early stage in the folding in response to the tensional stress on the outer part of the fold, and then was rotated with the fold. Where this rotation brought the cleavage into parallelism with the planes of movement, the cleav-

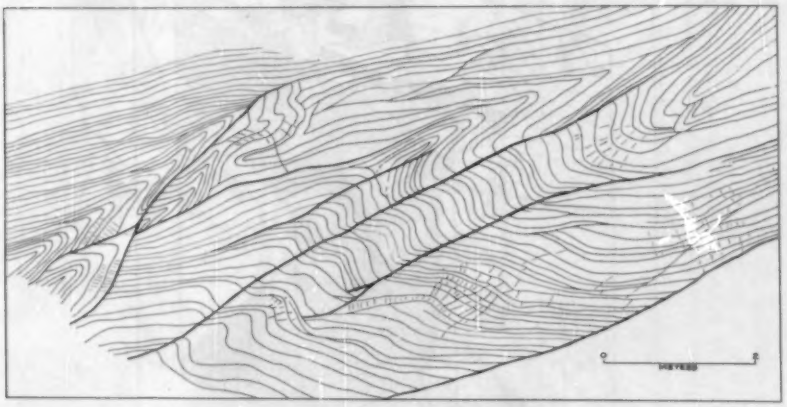


FIG. 4. Vertical face of bluff illustrating typical structure of the shale. Location: N—14760, E—10600. Observer looking N 32 W, 5 degrees downward, about parallel to the fold axes and lineation, both of which strike N 30 W, and plunge 12 north. Faults, shown by heavy lines, strike N 5 W and dip 30 W. Bedding and minor slips are shown by light weight lines. Cleavage is shown only where strong.

age was displaced rather than the bedding. This relation between bedding and cleavage holds throughout the area; namely, that the shale was folded along the planes best oriented to relieve the stress, which were bedding planes if they were oriented parallel to the general trend of bedding, but otherwise were cleavage or fault planes.

Thus, most of the isoclinal drag folds were rotated to such a position that their axial planes are parallel to the average trend of the bedding at their place in the major anticline, and consequently not parallel to the axial plane of the major anticline. However, the axes of the isoclinal drag folds are parallel to the axis of the major anticline.

Rhyolite.—Rhyolite is found nearby although not in the Frisco mine itself (Fig. 2). The rhyolite is pink to white, and contains about 5 percent of

quartz phenocrysts averaging 2 mm across in a fine-grained groundmass. Most of the rhyolite is in irregular, tabular bodies a few meters thick that repeatedly change in form from sills to dikes. The rhyolite is younger than the shale and the veins but older than the gravel, diabase, and basalt. It and the other younger rocks are probably of Tertiary age, as are thought to be most of the volcanic rocks in the region (17), but no direct evidence is known.

Gravel.—In many places, there is caliche-cemented gravel up to 10 m thick between the shale and the overlying basalt. Its outcrop is not large enough to show on the map. The gravel consists of pebbles, small boulders, and a little fine sand, cemented by calcite. The pebbles and boulders are of shale,

FIG. 5. Part of a small flexure fold with cleavage shearing the beds on the nose of the fold. Cleavage fans slightly and dips gently left. Location: N—19,950, E—10,360, on road from tramway angle station to South shaft.

limestone, rhyolite, and several kinds of andesite, at least some of which came from the mountains at Los Azules (Fig. 1) or farther away. The gravel unconformably overlies a gently-rolling erosion surface on the shale and is rudely bedded horizontally.

Diabase and Basalt.—Aside from unconsolidated sediments, the youngest rocks are basalt flows and diabase dikes that presumably fed them. The basalt is dark grey, hard, dense, and breaks with a conchoidal fracture. It consists of 85 percent feldspar and pyroxene, in the ratio of 3:1, 10 percent olivine phenocrysts, and 5 percent vesicles, most of which are partly filled with calcite. The dikes are coarser grained than the flows but similar in composition, except for containing more calcite, some as recognizable inclusions.

The basalt flows were poured out unconformably on a gently rolling sur-

face with a relief of about 50 m developed on the older rocks. The flows dip about 3 degrees eastward and the fronts of most flows face east. The diabase dikes mainly follow post-ore cross faults of about 10 m displacement, which extend continuously from the surface to the depth of mining.

Veins

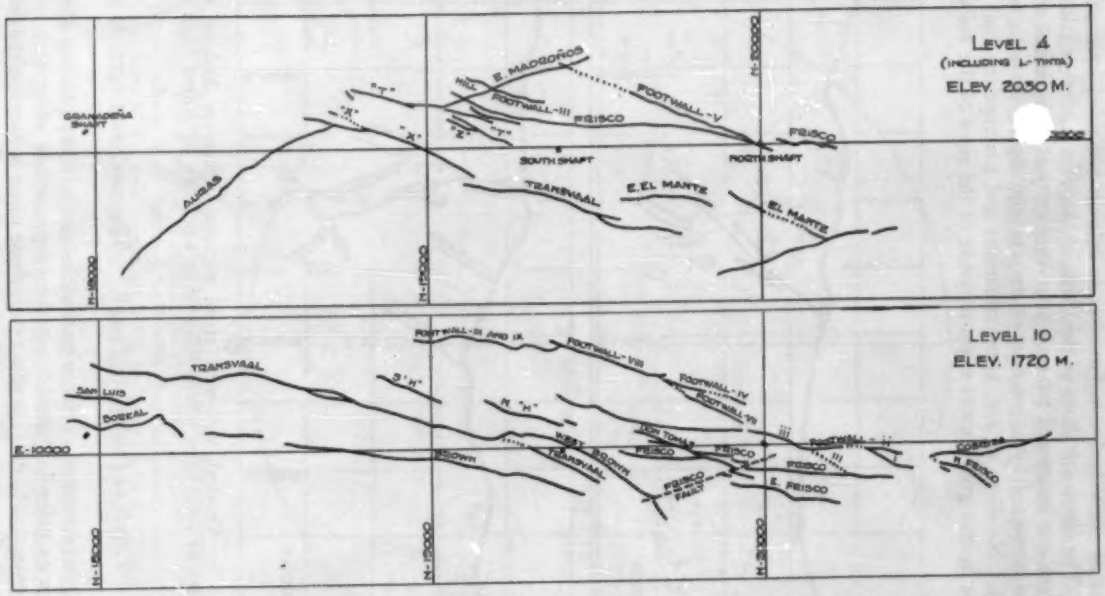
All the veins of the Frisco mine fill fractures, with little replacement of the walls, although breccia fragments within the veins are silicified, silicated, and replaced by sulfide minerals. The fractures are faults whose largest displacements are measured in a few tens of meters. Most veins are somewhat longer than deep. Those that carry ore are mostly from 0.8 to 2.0 m wide; veins between 2 and 5 m wide are very uncommon; and veins wider than 5 m occur only locally. About a quarter of a typical vein is less than 50 cm wide, ranging down to a knife-edge fracture. Even in the centers of oreshoots, veins commonly pinch to knife-edge fractures but many such fractures persist clearly enough to be followed to where the veins open out again.

The time of the fracturing and vein filling is unknown but was later than the deposition of the shale, which is probably Cretaceous, and earlier than the formation of all the other rocks, which are probably Tertiary.

Arrangement and Pattern of Veins.—The arrangement of the veins in the Frisco mine is illustrated by representative plans and cross sections (Figs. 6 to 9), which make clear that the veins are very regular in attitude, although more so in strike than in dip. Thirty-two principal veins are recognized, of which one, the Footwall vein, is not a distinct unit, but instead consists of several overlapping segments, designated by small Roman numerals, e.g., Footwall-i. Several smaller veins and many thin stringers are known but have supplied very little ore. They are all parallel to one or more of the principal veins. Except for the several segments of the Footwall vein, each vein is a distinct unit and veins with similar names are not to be taken as related in any way, unless explicitly stated.

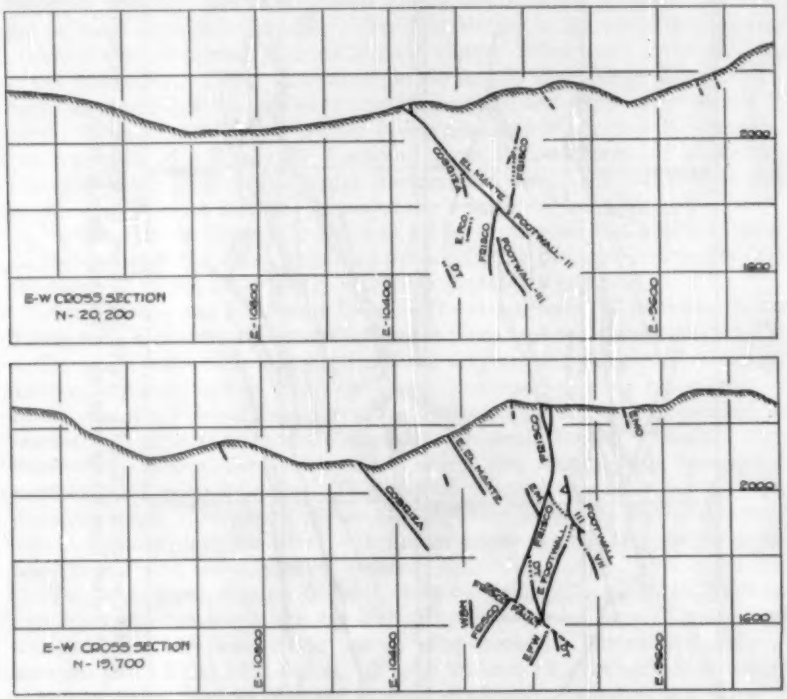
Two level plans, Figures 6 and 7, show the veins followed in workings on two representative levels, the 4th level, the highest being worked today, and the 10th; the 13th level is the lowest being worked. The vertical distance between levels 4 and 10 is 310 m. Except on level 13, development is largely complete within the area enclosed by mine workings. Crosscuts and diamond drill holes, not shown, have prospected most of the remaining ground and the chance of discovering a large new vein is small. Both the largest number of veins and the greatest length of drifting are on levels 7 and 10. Above and below those levels the area of the mine and concentration of veins gradually diminish. This arrangement is also illustrated by the cross section, Figures 8 and 9.

The outstanding feature about the veins is that each is nearly parallel to one of four ideal, imaginary planes. Thus, four sets of mutually parallel veins are defined. Tables 1 to 5 list all of the veins in each set, giving the name, abbreviation, attitude, total area, and area that is ore for each vein. The areas are measured in square kilometers and also as a percentage of the



FIGS. 6 AND 7. Plans of veins on levels 4 and 10. Veins are shown by solid lines where followed in drifts, by dotted lines where inferred. Crosscuts are not shown.

total area of all veins. The last column gives the percentage of the total area that is ore for an individual vein (number in column 5 divided by number in column 3). The areas are those of the plane of the vein surface if laid down flat. This area was measured for each vein on a vertical longitudinal section, and was then corrected by a function of the average dip of the vein to give the true area. Needless to say, approximations and assumptions had to be made, but the figures give a more exact measure of the sizes of the veins than



FIGS 8 AND 9. Vertical, east-west cross sections. Observer looking south. Veins are shown by solid lines where followed in workings, by dotted lines where inferred.

would adjectives such as "large" or "small." The maximum error is about 20 percent.

The average attitudes of all the veins may be compared by plotting normals to their planes as poles in Schmidt equal-area projection (Fig. 9a). Each point on the projection is the pole of a vein, whose name is listed in the margin and whose percentage area (from column 4 of Tables 1 to 4 with decimal omitted) is marked beside it. Seen in this way on the projection, the four sets of mutually parallel veins stand out, and when the common physical char-

acteristics of the members of each set are considered the four sets are unmistakable.

The area of a vein is but one measure of its importance; others are its volume, tonnage of ore, tonnage of contained metals, and indices combining two or more of these. But in a grouping according to attitude, area appears

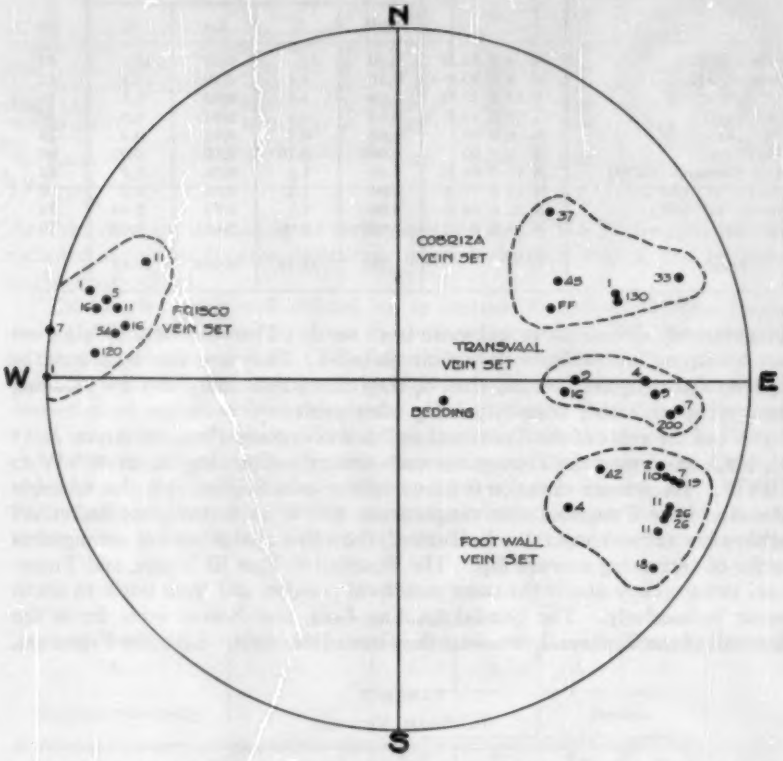


FIG. 9a. Schmidt equal-area projection (lower hemisphere) of veins in the Frisco mine. Poles represent normals to the veins; numbers give the percentage area (from column 4 of Tables 1 to 4 with decimal points omitted) of each vein and correspond to the vein names as listed in Tables 1 to 4. The average attitude of the bedding in the Frisco mine is also represented by a pole.

to be the measurement to consider, and for the mechanical interpretation of the vein-fractures, the area of a fracture is more significant than its width.

Of the four sets of veins, the Frisco set is the most sharply defined; Fig. 9a shows that for the stronger veins of the set the dips have nearly the same value, 76° E, whereas the strikes vary from N 5° E to N 25° E. From north to south in the mine, the average strikes of the various veins of the set

TABLE 1

FRISCO VEIN SET

1. Name and Abbreviation	2. Attitude	3. Total area	4.	5. Ore area	6.	7. %
		Km²	%	Km²	%	Ore
Frisco (FCO)	N 5 E 76 E	0.69	12	0.57	18	83
Brown (BN)	N 9 E 70 E	0.31	5.4	0.19	5.8	61
"Z" (Z)	N 13 E 77 E	0.09	1.6	0.05	1.5	56
"KL" (KL)	N 15 E 75 E	0.03	0.5	0.017	0.5	57
"A" (A)	N 8 E 90	0.04	0.7	0.01	0.3	25
"AG" (AG)	N 0 E 90	0.006	0.10	0.00	0.00	00
East Footwall (EFW)	N 11 E 68 E	0.09	1.6	0.06	1.9	67
North "H" (NH)	N 14 E 71 E	0.06	1.1	0.04	1.2	67
South "H" (SH)	N 25 E 68 E	0.06	1.1	0.02	0.62	33
"Q" (Q)	N 16 E 80 E	0.005	0.09	0.001	0.03	20
Totals		1.381	24.19	0.958	29.85	

progressively deviate more and more from north. The veins of the Frisco set are all strong and wide, with regular attitudes. They are also what may be called "throughgoing" veins, that is, they characteristically end by pinching or fraying out rather than by joining other veins.

All of the veins of the Transvaal set have essentially the same strike, N 5° E, but, considering the average for each vein, the dips range from 40° W to 70° W. Even more variation is found within an individual vein; for example the dip of the Transvaal vein ranges from 40° W to vertical, but individual strikes are rather constant. In Table 2, the veins of this set are arranged in order of decreasing average dip. The Footwall-ii, East El Mante, and Transvaal veins occupy nearly the same structural position and from north to south occur successively. The Guadalupe, San Luis, and Boreal veins lie in the footwall of the Transvaal vein near the Granadeña shaft. Like the Frisco set,

TABLE 2

TRANSVAAL VEIN SET

1. Name and Abbreviation	2. Attitude	3. Total area	4.	5. Ore area	6.	7. %
		Km²	%	Km²	%	Ore
East El Mante (EEM)	N 6 E 70 W	0.04	0.7	0.004	0.1	10
Transvaal (TR)	N 7 E 68 W	1.13	20	0.49	15	43
San Luis (SL)	N 3 E 63 W	0.05	0.9	0.013	0.4	26
Guadalupe (GD)	N 0 E 60 W	0.02	0.4	0.003	0.1	15
Boreal (BL)	N 0 E 42 W	0.05	0.9	0.02	0.6	40
Footwall-ii (FW-ii)	N 4 E 40 W	0.09	1.6	0.06	1.9	67
Totals		1.38	24.5	0.590	18.1	

TABLE 3

COBRIZA VEIN SET

1. Name and Abbreviation	2. Attitude	3. Total area	4.	5. Ore area	6.	7. %
		Km²	%	Km²	%	Ore
Cobriza (CB)	N 20 W 57 W	0.74	13	0.39	12	53
East Cobriza (ECB)	N 22 W 57 W	0.005	0.09	0.00	0.0	0
East Madroños (EMD)	N 20 W 75 W	0.19	3.3	0.11	3.4	58
Auras (AU)	N 32 W 45 W	0.26	4.5	0.09	2.8	35
Merced (MC)	N 48 W 55 W	0.21	3.7	0.04	1.2	19
Totals		1.405	24.59	0.63	19.4	

the Transvaal set is made up of throughgoing veins. The Footwall-ii vein is included in this set because its attitude is much closer to that of this set than to the Footwall set.

The Cobriza set is well defined but in attitude its individual veins range more widely from the average than the veins in other sets. The largest fault in the mine, the Frisco fault (FF), also belongs to this set. From north to south in the mine, the average strikes of the individual veins progressively deviate more and more from due north. Except for the East Cobriza, a very small vein lying in the footwall of Cobriza, all the veins in this set are large and have especially long and prominent outcrops. The outcrops of Cobriza and Merced (including closely associated veins) each extend for 1.4 km. The outcrop of East Madroños and Auras, veins which on the surface and upper levels follow the same structure, extends for 2.1 km, including the sub-

TABLE 4

FOOTWALL VEIN SET

1. Name and Abbreviation	2. Attitude	3. Total area	4.	5. Ore area	6.	7. %
		Km²	%	Km²	%	Ore
Footwall (FW)	N 20 E 70 W	0.62	11	0.47	14	76
El Mante (EM)	N 23 E 53 W	0.24	4.2	0.12	3.7	50
"M" (M)	N 18 E 68 W	0.01	0.2	0.006	0.2	60
East Bronces (EBC)	N 20 E 73 W	0.04	0.7	0.02	0.6	50
"T" (T)	N 20 E 75 W	0.11	1.9	0.07	2.2	64
North Frisco (NFCO)	N 25 E 75 W	0.06	1.1	0.02	0.6	33
Don Tomas (DT)	N 25 E 75 W	0.15	2.6	0.10	3.1	67
"X" (X)	N 27 E 75 W	0.15	2.6	0.12	3.7	80
Hill (HL)	N 30 E 75 W	0.06	1.1	0.05	1.5	83
West Brown (WBN)	N 36 E 80 W	0.10	1.8	0.09	2.8	90
West Bronces (WBC)	N 36 E 51 W	0.02	0.4	0.008	0.3	40
Totals		1.56	27.6	1.074	32.7	

outcrop below the basalt capping. The veins of the Cobriza set are all throughgoing veins.

The veins of the Footwall set dip consistently about 75° W but range in strike from N 18° E to N 36° E. The West Bronces vein, which is small and poorly defined, is included with this set for convenience although its attitude is very different from the average. The El Mante vein also deviates widely from the average attitude because it is a linking vein between the Footwall and Transvaal set and is continuous with the Footwall-ii vein, from which it is arbitrarily separated at Level 9. In sharp contrast to the veins of the other sets, the veins of the Footwall set are not throughgoing. Instead they split from other veins and many of them rejoin other veins and therefore are linking veins.

Relation of Vein Structure to Shale Structure.—Within a vein fracture in the Frisco mine the angle between the fracture and the bedding of the shale

TABLE 5

SUMMARY OF VEIN SETS

1.	2.	3.	4.	5.	6.	7.
Name	Attitude	Total area		Ore area		%
		Km²	%	Km²	%	Ore
Frisco set	N 7 E 76 E	1.381	24.19	0.958	29.85	69
Transvaal set	N 5 E 65 W	1.38	24.5	0.590	18.1	43
Footwall set	N 25 E 75 W	1.56	27.6	1.074	32.7	69
Cobriza set	N 25 W 50 W	1.405	24.59	0.63	19.4	45
Totals		5.726	100.88	3.252	100.05	57

Note: Percentages do not total 100 due to rounding.

is the most important factor governing vein strength. In general the wide parts of the veins stand at a large angle to the shale bedding. Evidently, the stress that fractured the rock opened wide, persistent vein fractures only where it could not be dispersed by small displacements along favorably oriented bedding planes. An exactly comparable relation between fissure veins and slate was pointed out in the Coeur d'Alene district by McKinstry and Svendsen (23).

The east-dipping fractures of the Frisco vein set stand at 90 degrees to the average attitude of the bedding. They contain the veins that are the widest and the most regular in width. The west-dipping fractures of the Footwall vein set stand at an average angle of 60 degrees to the bedding and contain the next-strongest veins. The fractures of the Transvaal and Cobriza sets, which also dip west, on the whole make angles of 35 to 50 degrees with the bedding and their veins are weaker than the others. A measure of the relative strength of veins in the different sets is given by Table 5, which shows that 69 percent of the total area of veins in the sets standing at large angles

to the bedding has sufficient width and mineralization to be ore, but only 44 percent of the total area of the veins in the sets at lower angles.

Within a single vein, the influence of the angle between the vein and the shale bedding is also seen everywhere and on every scale. Commonly, a vein thins or ends by gradually flattening to where it is parallel to the bedding of the shale; whereupon, the vein-fracture passes into the shale and becomes

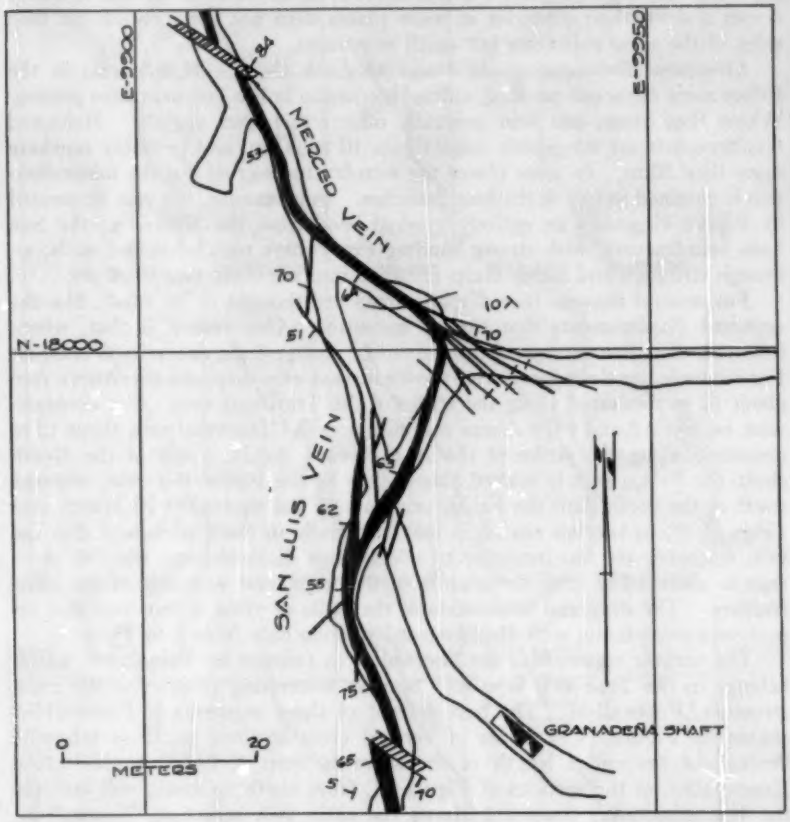


FIG. 10. Junction between the San Luis and Merced veins, level 8.

either a tight veinlet about 10 cm wide, in many places with high grade sulfide minerals but no gangue, or a knife-edge seam that may pinch out altogether. In some places, a vein flattens for a stretch, and then stands up again and regains its strength. The axis of inflection of the plane of the vein may have any direction and no rules are known, but generally its plunge is not far from horizontal.

There is a little drag on the beds next to some veins but more commonly there is none (Figs. 12 and 16). Where present, the drag is consistent with normal displacement on the fractures. In most places, the beds have been displaced noticeably by the fractures but correlations of beds across the drifts, though uncertain, suggest that the displacements are less than the height of the drifts. Where veins pinch out the shale beds commonly cross the workings with no displacement. Furthermore, even where beds cannot be traced across a drift, their attitudes in more places than not are identical on both sides of the vein, indicating but small movement.

Structural Relations of the Veins to Each Other.—Many veins in the Frisco mine cross one another, although crossing is less common than joining. Where they cross, one vein generally offsets the other slightly. Measured displacements are commonly small, from 10 to 20 m, and probably nowhere more than 30 m. In some places the vein-fractures cross but the mineralization is confined to two of the four branches. For example, the vein illustrated by Figure 10 makes an entirely gradual bend from the Merced to the San Luis vein-fracture, with strong banding everywhere parallel to the walls, although stringers and minor faults continue into the other two branches.

For several reasons true displacements are thought to be small, like the apparent displacements that can be measured. One reason is that, where followed, displacements generally die out or change from one vein to another. For example, on the upper levels the Transvaal vein displaces the Auras vein about 12 m measured along the strike of the Transvaal vein. But contrariwise, on levels 8 and 9 the Auras vein displaces the Transvaal vein about 15 m measured along the strike of the Auras vein. Again, north of the North shaft, the Frisco vein is faulted about 30 m by the Footwall-ii vein, whereas south of the north shaft the Frisco vein cuts off the equivalent El Mante vein (Figs. 8, 9). Another reason is that, especially in the direction of dip, the vein fractures are too irregular to allow large displacements without more than is observed of drag, brecciation of the walls, and widening of the vein-fracture. The drag and brecciation of the walls of veins is less than that on post-vein cross faults with displacements ranging only from 5 to 15 m.

The various segments of the Footwall vein (except for Footwall-ii, which belongs to the Transvaal vein set) bear an interesting relation to the main structure, Footwall-iii. The best defined of these segments is Footwall-ix, shown by Figure 11, a series of vertical cross sections at 25 m intervals throughout the entire length of the segment from N-19,500 to N-19,150. Examination of the sections of Figure 11, from north to south, will indicate the vein structure. Section 1 shows the main vein structure, Footwall-iii, with a few gentle rolls (by "roll" the writer means a change in the attitude of the vein surface parallel to a more or less horizontal axis). There is no sign of the Footwall-ix segment except for the small Footwall-viii segment, which may be continuous with Footwall-ix. Footwall-ix is first recognized on section 2, where it appears as an almost vertical roll in the Footwall-iii structure, which is still continuous. Sections 3 and 4 show that Footwall-ix has split from the hanging wall of Footwall-iii but going downward is still a continuous structure. At the place shown in section 5, Footwall-ix is a sepa-

rate structure that plunges steeply downward toward the south, as shown by sections 6 and 7. The part of the vein segment illustrated by these last sections evidently "broke through" both the hanging and footwalls of the main Footwall-iii vein and not only is the best-formed structure but also carries

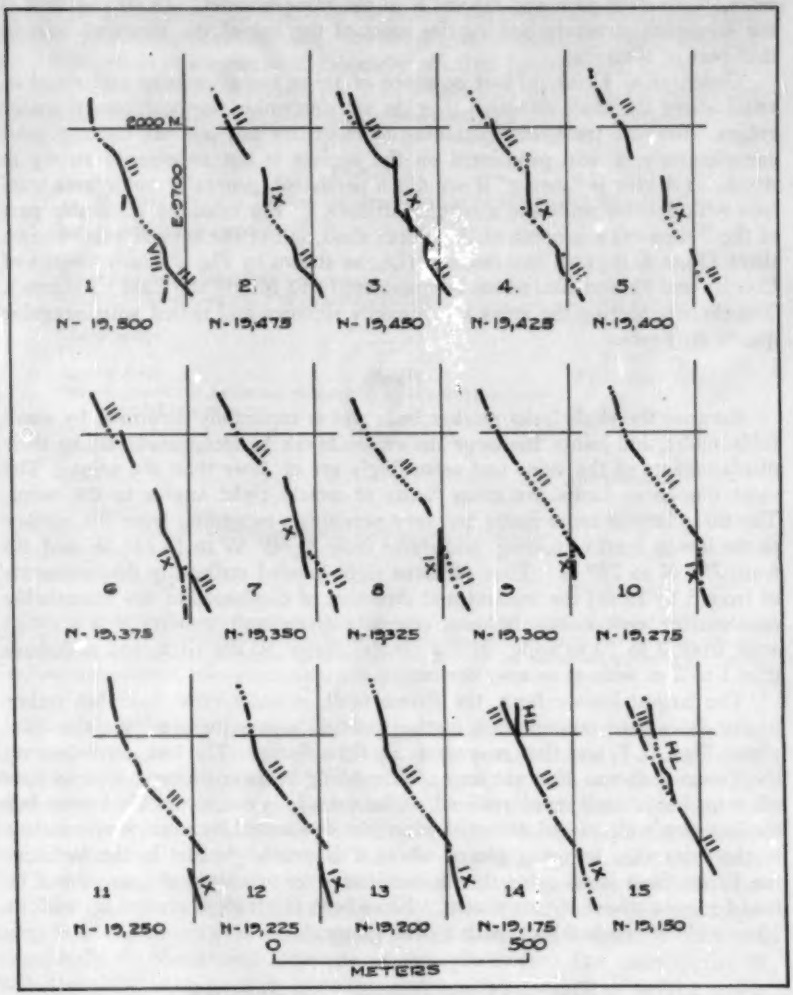


FIG. 11. Vertical, east-west cross sections through the Footwall vein from N—19,500 to N—19,150. Observer looking south. Veins are shown by solid lines where followed in workings, by dotted lines where inferred.

most of the ore. Yet still farther south, between sections 8 to 14, Footwall-ix is again merely a split from Footwall-iii, although here from the foot rather than from the hanging wall as where shown in sections 3 and 4. Finally, on section 15, Footwall-ix is seen to have rejoined the main structure and lost its identity. To summarize, the Footwall-ix segment appears as a roll in the main Footwall-iii vein and rejoins it in the same manner. In its center it is the dominant structure and carries most of the ore of the Footwall vein in that part of the mine.

Outcrops of Veins.—Most outcrops of veins are prominent and stand in relief above the shale although they do not determine the positions of major ridges. Because the veins containing more quartz and less ore outcrop most conspicuously, a vein prominent on the surface is not necessarily strong at depth. (A vein is "strong" if ore fills a persistent, generally continuous fracture with definite walls and a regular attitude.) For example, a sizeable part of the Frisco mine is north of the North shaft, but of the several veins known there (Figs. 6–8) only two outcrop (i.e., as shown by Fig. 2, short lengths of Cobriza and Capitaneña, which is equivalent to El Mante and East El Mante). The shale bordering the veins is commonly silicified and netted with irregular quartz stringers.

Faults

Because the shale lacks marker beds and is intricately deformed by small folds, faults, and joints, the large known faults can be recognized only by their displacements of the veins and accordingly are all later than the veins. The most numerous faults are cross faults at nearly right angles to the veins. The three largest cross faults are very persistent, extending from the surface to the lowest level of mining, and strike from N 60° W to N 75° W and dip from 75° N to 75° S. They all have right-handed strike-slip displacements of from 5 to 15 m; the amount and direction of displacement are remarkably constant for each fault. In most places, a cross fault consists of a crushed zone from 2 to 10 m wide, with a central cavity 50 cm wide, and a diabase dike 1 to 2 m wide at or near the center.

The largest known fault, the Frisco fault, is not a cross fault but rather is the downward continuation of the Cobriza vein structure (see the level plans, Figs. 6, 7, and the cross sections, Figs. 8, 9). The last movement on the Frisco fault was after the time of vein filling because the fault sharply cuts off veins but is itself unmineralized. The net slip is not accurately known but the hanging wall moved about 35 m either downward or northward relative to the footwall. In many places where it is nearly parallel to the bedding, the Frisco fault is no more than a centimeter or two wide and so cannot be found except where it cuts a vein. Elsewhere the fault is a zone up to 5 or 10 m wide of crushed rock with a little gouge.

Mineralogy and Internal Vein Structure

The mineralogy of a typical unoxidized vein in the Frisco mine is simple (Table 6). Most of the content of valuable metals is in the simple sulfides

sphalerite, galena, and chalcopyrite, which occur together with pyrite in every vein. The gangue minerals are mainly quartz, calcite, fluorite, and silicate minerals of the kinds common in skarn deposits.

Hypogene Sulfide and Other Metallic Minerals.—The common members of this group are sphalerite, galena, chalcopyrite, pyrite, arsenopyrite, gold, hematite, and scheelite. In addition, the writer has doubtfully identified small amounts of bornite, covellite, and tetrahedrite in polished sections, and has seen a few grains of magnetite in intensely silicated fragments of shale. The occurrence of silver is not known but it is presumably in or closely associated with the galena, for the lead concentrate is silver rich.

TABLE 6

MINERALOGY OF A TYPICAL UNOXIDIZED VEIN IN THE FRISCO MINE

Sulfide and other ore minerals:		
Gold	0.5	grams/ton
Silver (mineral composition uncertain)	150	grams/ton
Sphalerite (including 9% FeS in solid solution)	14	percent
Galena	6	percent
Chalcopyrite	2	percent
Pyrite	2	percent
Arsenopyrite	0.7	percent
Bornite, covellite, hematite, magnetite, tetrahedrite, scheelite, total less than	0.3	percent
Gangue minerals:		
Quartz	33	percent
Calcite	9	percent
Fluorite	11	percent
Silicate minerals: diopsite, actinolite, epidote, ilvaite, chlorite, biotite, sericite	22	percent
Total	100	percent

Note: This table lists the names of observed minerals and amounts calculated from incomplete assays of ore. Amounts are approximate as some elements, in particular fluorine, are not determined directly by assay. Some elements not included in the tabulated minerals are found in various mill products, but corresponding minerals have not yet been identified.

The *sphalerite* is not pure ZnS, but instead contains an average of about 6 percent Fe and about 0.6 percent Cu in typical samples carefully handpicked under a binocular microscope. Twenty such samples vary widely in composition with no discernible regard for location by veins or depths. Most of the iron is evidently in solid solution in the sphalerite, which is of the dark *marmatite* variety. Some of the copper may be in solid solution also, but much of it is intimately intergrown with the sphalerite in the common emulsion texture; that is, all the sphalerite examined in polished sections contains blebs and rods of chalcopyrite, or rarely pyrite, most of which are strongly oriented, undoubtedly by the crystal structure of the sphalerite. The chalcopyrite is most abundant in certain layers that are parallel and close to the grain boundaries.

Most of the *galena* is intergrown with the other sulfide minerals but some is in fine grains that preferentially replace certain layers of the shale.

Much of the *chalcopyrite* veins or rims grains of pyrite or arsenopyrite. With an increasing amount of chalcopyrite, the texture becomes that of "islands" of pyrite or arsenopyrite in a "sea" of chalcopyrite. Chalcopyrite also occurs as rods and blebs in grains of sphalerite, and as replacements of silicate minerals.

The *pyrite* content ranges widely, from less than 1 percent up to about 10 percent. Almost all of the pyrite in the veins is in euhedral cubic crystals, which range from 3 mm to 3 cm across and which commonly are veined and partly replaced by the other sulfide minerals. The shale also contains pyrite, some in disseminated crystals, but most in thin veinlets or as coatings on joint surfaces. Pyrite is widespread throughout the shale but is most abundant near the veins.

Arsenopyrite is in euhedral to subhedral crystals 0.5 to 2 mm across, mostly concentrated in local patches in the veins on the lower levels, where it may be 50 percent or more of the vein matter.

Gold is widespread although nowhere abundant and seldom visible.

In a few polished sections, *hematite* of the *specularite* variety is seen in small, ragged flakes, close to pyrite crystals.

Scheelite in grains less than a millimeter across is sparsely disseminated through the veins in some places. Its occurrence is not well known but it is probably most abundant on the lower levels.

Hypogene Gangue Minerals.—Quartz, calcite, and fluorite are found throughout the veins. The silicate gangue minerals, on the other hand, are abundant only in some places, and their overall proportions and abundance relative to the other minerals are unknown.

The vein *quartz* ranges from clear, colorless, comb quartz which lines vugs, to dull, greenish quartz, which replaces fragments of shale.

Most of the *calcite* fills interstices between grains of other minerals and some is in veinlets that cut all the other minerals. On the grains measured, the lowest index of refraction of the calcite is 1.486, indicating that it is essentially pure $CaCO_3$.

The *fluorite* is largely white and fine-grained. Most of it fills interstices of minerals deposited earlier but some crystals line vugs.

Diopside is both common and abundant, particularly on the lower levels, where one-half to three-fourths of the shale fragments within a vein may be altered to diopside. The composition varies but is close to that of the variety *salite;* that is, the ratio Mg : Fe is about 1 : 1.

Actinolite is widespread throughout the mine but is not so conspicuous as diopside and is probably less abundant. In composition, it ranges from the pure magnesian end member, tremolite, to actinolite with a ratio of Mg : Fe of about 4 : 1.

Epidote, although not abundant, is the most widespread silicate mineral and is found throughout the mine, even at a distance of several meters or more away from the veins.

Ilvaite is common, although nowhere abundant. It is in lens-like masses about 5 cm long, mostly in intensely silicated fragments of shale within the veins.

A few scattered flakes of *biotite, chlorite,* and *sericite* are visible in thin sections.

Supergene Minerals.—Near the surface all the veins are oxidized, but because they are not mined at present the writer has not studied them in detail. The oxidized ore is commonly vuggy, friable, and earthy, with a low density and residual boxworks, some of which have characteristic crystal shapes. The following supergene minerals have been reported, mostly by Deshler (6, p. 406) when the oxidized veins were being worked: anglesite, azurite and malachite, bornite, cerargyrite, cerussite, chrysocolla, covellite, gypsum, jarosite and plumbojarosite, limonite, massicot, mimetite, pyromorphite, silver, smithsonite, vanadinite, wulfenite.

Internal Vein Structure.—A typical vein in the Frisco mine (Fig. 12) is bounded on either side by regular, parallel walls, which are frozen to the vein matter. For a meter or two on each side of the vein, the shale country rock is silicified, pyritized, and slightly silicated, and contains sub-parallel stringers about 1 cm wide of quartz or calcite. Half or more of the vein is filled with irregularly shaped, partly-rounded breccia fragments of shale, which range in size up to about 1 m across and were presumably supported by the walls before the vein was filled. The sizes and arrangements of the fragments are so different that within a single stope all variations may be observed from typical ribbon structure through typical book structure to a chaotic structure. The fragments are more intensely silicified and silicated than the country rock and are replaced in part by a sufficient bulk of sulfide minerals to make up more than one-half of the ore of the vein. The remainder of the sulfide and gangue mineral matter cements and encrusts the fragments but filling of the original open spaces was incomplete and vugs up to 15 cm wide remain open. The crustiform deposition of the mineral grains produced bands, most of which are asymmetrical and broken, indicating that the vein was reopened during filling. Almost all of the sulfide mineral matter is confined within the vein, although a few grains are disseminated in the walls for a meter or two on either side.

The shale fragments, particularly on the upper levels, may be replaced by delicately layered minerals and, in addition, their surfaces may be crustified with layered minerals (Fig. 13). Where well developed, such layering, which is produced by replacement and open space filling acting together, gives rise to the structure called *caracol* (Spanish for "snail").

Oreshoots

Localization.—Ore in the Frisco mine is restricted to the veins; the country rock contains little or none. The oreshoots are irregular bodies that in longitudinal section approach ellipses with their long axes horizontal or gently plunging. The main controls of oreshoots are wall rock composition and vein and shale structure.

Wall rock composition influences the location of oreshoots somewhat, although to an unknown degree, as detailed work on this part of the geology is lacking so far. More silicate mineral matter appears to have formed where

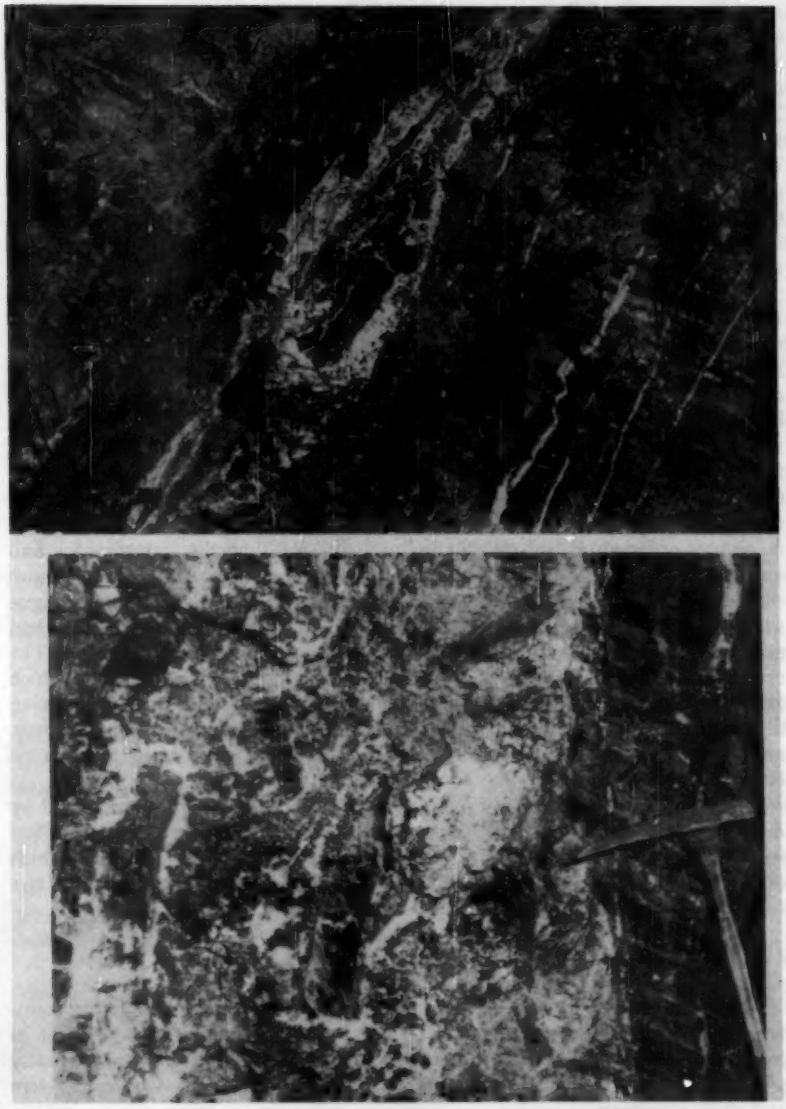


FIG. 12. Two examples of typical vein structure. The upper vein is 60 cm wide and dips 55° E. The black spots are drill holes. The wall rock is fractured, with sub-parallel quartz stringers in the footwall. The shale is bleached and silicified about 10 cm on either side of the vein. The center of the vein contains a

FIG. 13. *Caracol* vein structure. The diameter of the rounded *caracol* at right is 40 cm; long axis of the photograph is parallel to strike of vein. Part of the back of a drift on the "KL" vein, level 5, South drift, at N—187,774.

the shale was initially more limy and perhaps more iron-rich, and many of the grains of sulfide minerals replaced grains of silicate minerals.

Structural control is demonstrated by the following facts. The strongest veins, which contain most of the best oreshoots, are those standing at a large angle to the shale bedding. Within a single vein, the oreshoots tend to lie in the parts with attitudes near the average for the vein. Most of the better oreshoots are in veins of medium rather than excessive widths. Where a vein is very wide the metal content per square meter of vein surface area is little or no greater than in adjacent parts where the vein is narrower; therefore where a vein is wide the grade tends to be low. Finally, most oreshoots are near the center of the mine, for reasons stemming from the origin of the vein fractures, a subject taken up below.

The Cobriza vein exemplifies the structural control of oreshoots. The relationship between the attitude of this vein and the location of its oreshoots

white gangue of quartz, fluorite, and a little calcite, surrounding breccia fragments of shale, which are intensely silicated with diopside. Grecia vein, level 13, South drift 126—S at N—19,850, looking southward at face.

The lower vein is shown in more detail. The irregularity in detail of the wall is well shown, as well as breccia fragments, most of which are silicated and partly replaced by sulfide minerals. Esparta vein, level 12, South drift 71—S, at N—19,700. These veins, while typical, have been found only recently and so are not listed in Tables 1 to 4.

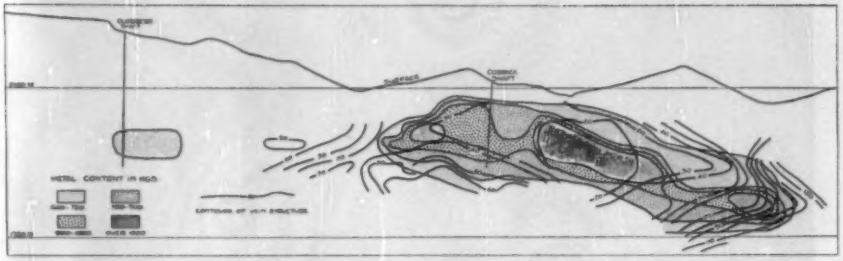


FIG. 14. Longitudinal section of the Cobriza vein, showing contours of vein structure and metal content. Contours of vein structure show the horizontal distance in meters of the vein from a reference plane with an attitude of N 16 W 57 W, lying in the hanging wall of the vein. Contours of metal content and dotted patterns represent the total kilograms of lead, copper, and zinc per square meter of vein surface, projected to a vertical plane striking N 16 W. A tonnage-volume factor of 3 metric tons per cubic meter is assumed.

is brought out by Fig. 14, which shows by contours the attitude of the vein surface and the variation in metal content. The attitude of the vein surface is represented by contours showing the distance every part of the vein lies from a reference plane standing at the average attitude of the whole vein. Thus, flat areas represent parts of the vein with attitudes approaching the average; on the lower levels the "hillside" facing upward represents a part of the vein with a dip steeper than the average; and on the upper levels to the

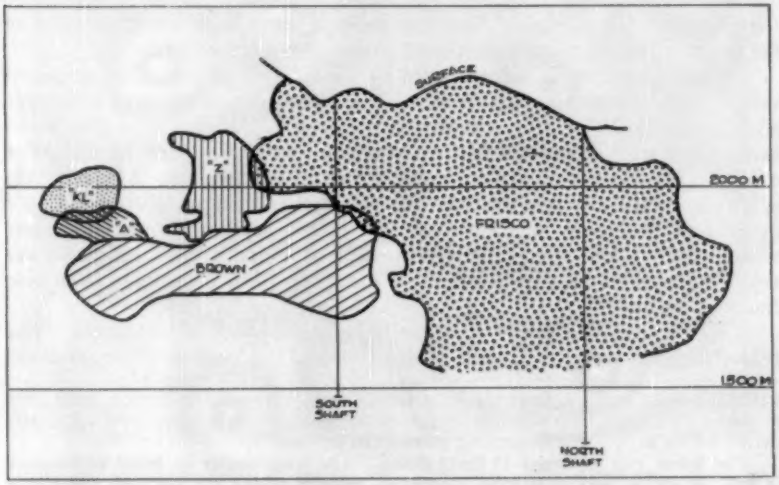


FIG. 15. Complementary oreshoots. Longitudinal section of oreshoots of closely associated veins of the Frisco set. The oreshoots of different veins are shown by different patterns.

north the "hillside" facing downward represents a part of the vein with a dip flatter than the average. Metal content is represented likewise by contours that show the variation in combined kilograms of lead, copper, and zinc per square meter of vein surface area. (Gold and silver are not included because these metals, although valuable, make up only an insignificant tonnage.) Comparison of the two sets of contours indicates the correspondence between parts of the vein with nearly average attitudes and parts with high metal contents. Particularly at the north end of the oreshoot, the poorer ore is on the "hillsides" where the attitude of the vein deviates from the average.

The grade of the Cobriza vein is not proportional to the width. On the contrary, where the vein is widest, assay values of combined lead, copper, and zinc are lowest, whereas where the assays are highest, on the lower levels near the northern end of the oreshoot, the vein is narrow. These facts suggest that the vein was prepared everywhere to receive all the metal available and that where the vein is wide the metal-bearing minerals were dispersed so that assay values are lower but total metal content is equal to that in places where the vein is narrow.

The writer has studied zoning of metals within the oreshoots but has reached no clear conclusions, except that the metals are irregularly distributed within individual veins in distinct shoots that do not directly correspond with the oreshoots. For the mine as a whole, there is evidence that in the ore-bearing parts of the veins, (1) gold and copper content decreases with depth; (2) silver content at first decreases with depth and then, on the lowermost levels, increases; and (3) lead and zinc content at first increase somewhat with depth, but then decrease on the lowermost levels.

Complementary Oreshoots.—The term "complementary oreshoots" is used to designate oreshoots that in longitudinal section appear to be continuous although actually the ore fills two or more veins. They are common where veins overlap, particularly where the veins belong to the same set and are close together. The clearest example is afforded by several veins of the Frisco set (Fig. 15). Recognition of complementary oreshoots aids development of new ore because superposition of longitudinal sections of neighboring veins reveals undeveloped ground. Complementary oreshoots resulted, the writer believes, from the mineralization of neighboring vein-fractures that opened so that the sums of the widths of the fractures, as viewed in longitudinal section, were the same throughout.

Ending of Oreshoots and Veins.—The veins of the Frisco mine end by fraying out into "horsetail" structures, by pinching to knife-edge fractures, or by joining other veins. Oreshoots end because the vein ends or because, although the vein persists, the mineralogy changes.

For example, the Cobriza vein appears to fray out into a horsetail structure below level 10 at the north end of the mine. There, the vein between levels 9 and 10 averaged 1.2 m in width and contained 24.4 percent combined lead, copper, and zinc. But on level 11, the drift followed a vein that averaged only 0.9 m in width with 12.7 percent, over less than half the length of the vein on level 10, to which it is connected by a raise following a continuous vein. On level 11, the bulk of the valuable metals are spread through the

shale and many subsidiary stringers, observed in two crosscuts and in core from several diamond drill holes. If all the stringers were gathered together, the resulting vein would be comparable in width and grade to the vein mined above level 10.

Where a vein pinches to a knife-edge fracture, there is a distinct change in vein structure and mineralogy. The gangue becomes mainly or entirely calcite, sulfide minerals become sparse, breccia fragments and the walls are but little altered. An example is shown by Figure 16 at a place where drifting was stopped because the vein narrows to 15 cm and contains only about 2 percent combined lead, copper, and zinc in a gangue of quartz and calcite with a larger than usual ratio (about 1:1) of pyrite to ore minerals. In the part of the vein pictured at the top and bottom of the photograph, the gangue is clean and crustified, suggesting open-space filling, but in the center the gangue surrounds incompletely replaced fragments and ribbons of shale, indicating that this part of the vein formed largely by replacement.

Veins change in both internal structure and mineralogy on the lower levels of the mine, although narrowing with depth is uncommon. Veins at depth have more-tightly frozen walls, fewer vugs, less caracol and banded structure, and more alteration minerals. Furthermore, many veins at depth are more poorly defined, with their boundaries becoming a zone of ramifying quartz stringers. Some veins show a marked decrease in the proportion of ore minerals accompanied by a change from "live-looking" to "dead" silicification quartz, a feature which, as Wisser (45) and others point out, is found in many veins below the ore. It is difficult to state exactly what constitutes the very distinct change from live-looking to dead quartz but it evidently is a change from quartz that either fills open spaces or completely replaces shale fragments to quartz that only incompletely replaces shale fragments. At depth, fluorite also increases sharply in amount, and more pyrite and arsenopyrite are also present, although arsenopyrite is nowhere abundant. The sulfide and gangue minerals become coarse at depth and crystals reach the size of those in pegmatites. A similar occurrence is reported at Santa Barbara where Schmitt (31) suggested that coarsening of grain size is an indication of oreshoot bottoming, a conclusion that finds some support in the evidence at the Frisco mine.

None of these changes appears to occur at a particular elevation, as some of the earlier geologists suggested. Instead, the changes depend on the attitude of the vein, its location, its internal structure, and the nature of the wallrock.

An example of the change with depth is the Brown vein, where the grade of the ore decreases abruptly below level 10. Although workings on level 10 and above followed a typical well-mineralized vein, long drifts on levels 11 and 12 followed a vein that instead was like the face pictured by Figure 17, which is largely white quartz with a very little fluorite. Black to grey fragments of shale are veined and nearly completely replaced by cloudy ribbon quartz, especially near the center of the vein. The hanging wall is sharp but the footwall, not shown by the photograph, consists of ramifying stringers. Most of

FIG. 16. "Z" vein at face where drifting was stopped. The vein is 15 cm wide and dips 85° E. The white gangue is quartz and calcite, and grey matter is largely shale and minor sulfides. Location: Level 5, South drift, at N—18,875, looking south at face.

FIG. 17. Brown vein, strong but low grade (6% combined Pb, Cu, Zn). The full width of vein, 1.6 m, is shown. Location: Stope 25 m above level 11, at N—19,400, looking northward at vertical face.

the sparse sulfide grains are disseminated throughout cloudy ribbon quartz, rather than through those shale fragments that are only slightly replaced.

Most oreshoots end laterally because the veins end; that is, the change is a structural one. On the other hand, vertically, and especially where bottoming, most oreshoots end by a change in mineralogy, except for those that end by joining other oreshoots. For example, the oreshoot on the Brown vein bottoms because of a change of mineralogy alone (Fig. 17). Again, at the surface, the Capitaneña, "X," and Transvaal veins are for the most part very low grade although strong, and the oreshoots begin at depth owing to an increase in the proportion of ore minerals. Because oreshoots end in a different manner vertically than laterally, an explanation for their form with length greater than height is offered. A reason for the difference is not known; a zone of flat-lying shale may have been chemically favorable for ore deposition, but so far evidence is wholly lacking. To learn the reason is economically

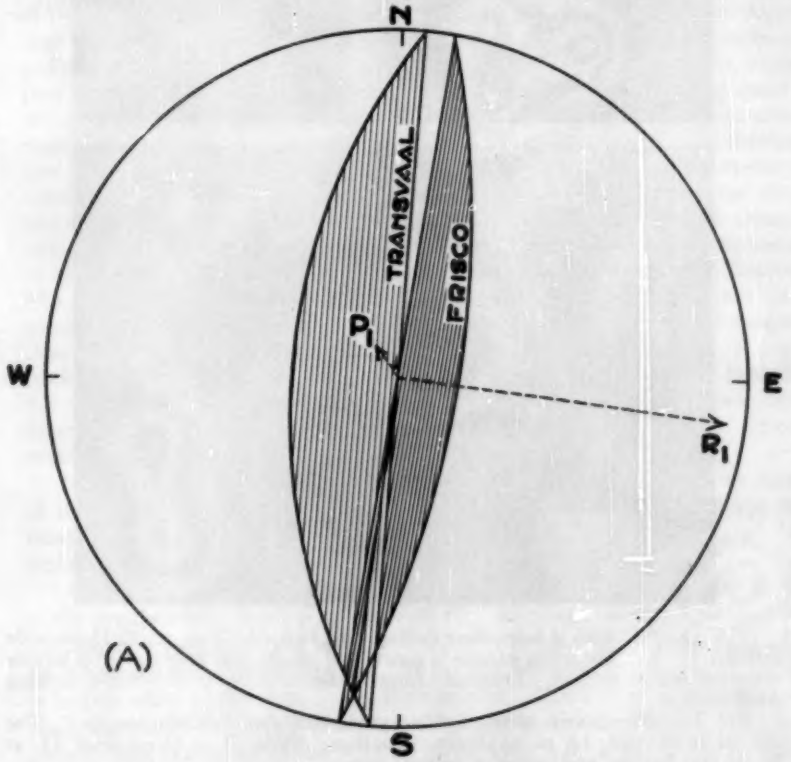


FIG. 18—*Continued on next page.*

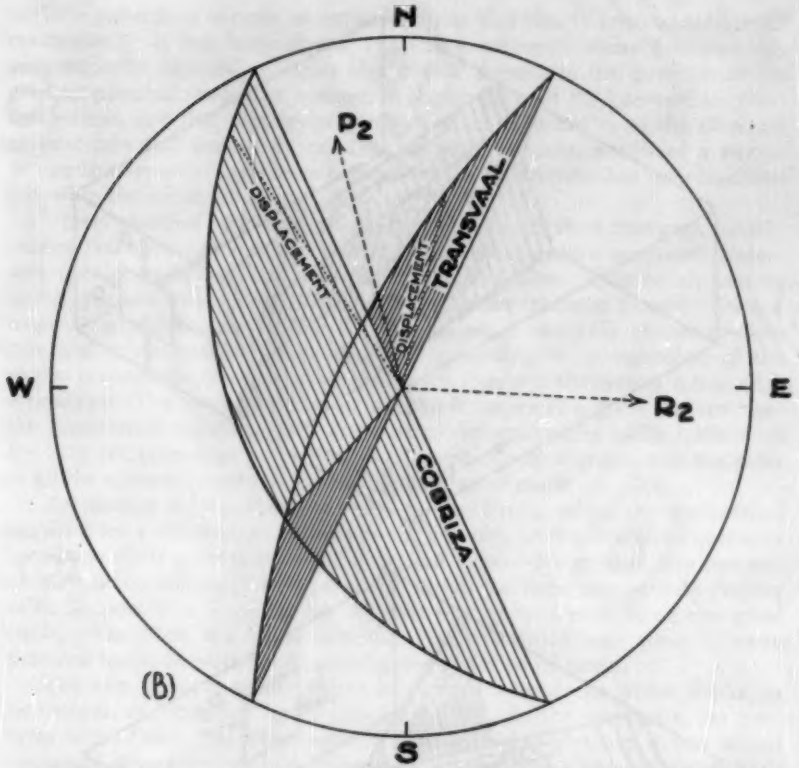


FIG. 18. Deformation scheme. Schmidt equal-area projections (lower hemispheres). *A* shows the planes of fracturing (parallel to the veins of the Frisco and Transvaal vein sets) of the first stage of deformation and the orientations of the greatest (P_1) and least (R_1) principal stress axes during the first stage. *B* shows the planes of fracturing (parallel to the veins of the Footwall and Cobriza sets) of the second stage of deformation, and the orientations of the greatest (P_2) and least (R_2) principal stress axes during the second stage; it also shows the directions of displacement on the fractures of the second stage. In each stage, the intermediate principal stress axis (Q_1 or Q_2) is, of course, the line of intersection of the two planes.

important because if an oreshoot is controlled by the wall rock, bottoming may be only local and another oreshoot lie below if the vein persists.

Origin of the Vein Fractures

General Theory.—Where natural fractures in the earth form a discernable pattern, rather than standing apparently at random, the fractures may generally be interpreted as two or more sets of conjugate shears, or, in a few places, as conjugate shears with an associated set of tension fractures. (This

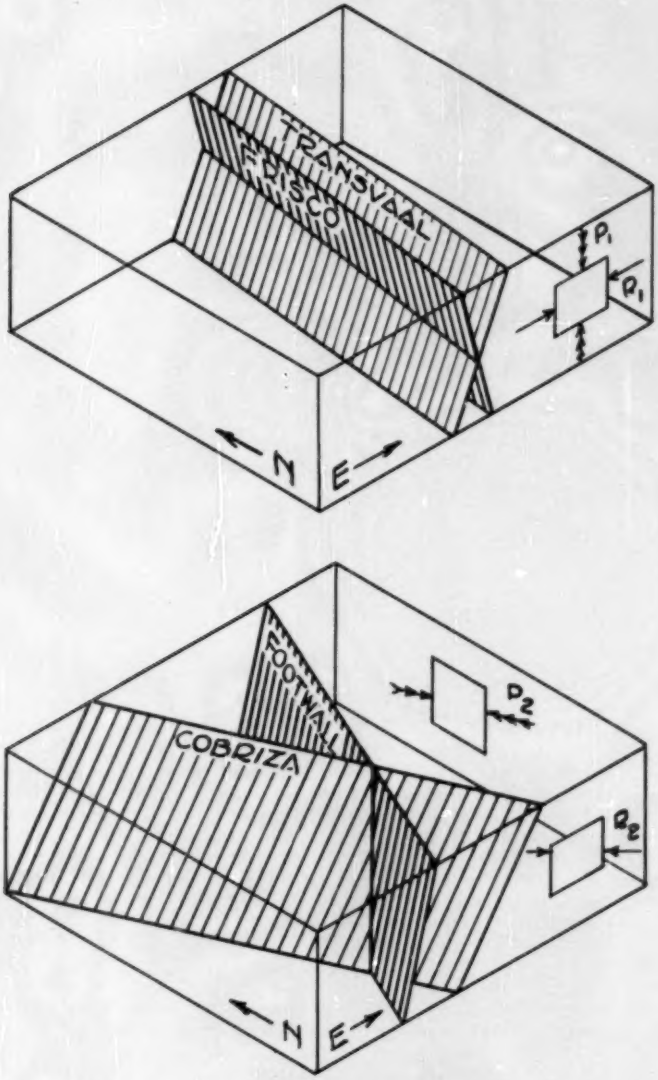


FIG. 19. Deformation scheme. Isometric block diagrams. The upper diagram shows the planes of fracturing (parallel to the veins of the Frisco and Transvaal sets) of the first stage of deformation and the orientations of the greatest (P_1) and least (R_1) principal stress axes, both of which lie nearly in an E-W vertical plane. The lower diagram shows the planes of fracturing (parallel to the veins

neglects patterns of arcuate or radial fractures that clearly form under special conditions.) It has been shown (12) that conjugate shear fractures are symmetrically disposed at angles of about 30 degrees to the direction of the greatest principal stress and intersect in the direction of the intermediate principal stress, and that tension fractures stand at right angles to the direction of least principal stress. In addition to these fractures, shears of a second or even higher order may form once the stress distribution has been modified following the initial rupturing (21).

Unless modified by inhomogeneity of the rocks, all these fractures, namely tension fractures and shears of the first and higher orders, necessarily intersect (projected if need be) in mutually parallel lines. This parallelism is, in fact, the sole geometrical result requisite for the fractures formed during a single-stage deformation where the orientation of the axis of intermediate principal stress remains the same. The parallelism holds regardless of the angles between the fractures, and even if the fractures themselves rotate after formation. The test of whether or not the fractures of a given pattern meet the geometrical requisite for a single-stage deformation is easily made with the Schmidt equal-area projection—agreement simply requires that the poles of all the observed fractures lie on the same great circle.

Application to the Frisco Mine.—In the Frisco mine, the geometrical requisite for a single-stage deformation is not met, as the Schmidt equal-area projection of the poles of the veins (Fig. 9a) shows. Necessarily, any two sets of veins lie on one great circle, and, moreover, the three sets of west-dipping veins lie close to a great circle. All four sets by no means lie on one great circle. Therefore, the writer concludes that fracturing took place in more than one stage, in response to a changed orientation of stress.

The vein fractures of the Frisco mine were formed, the writer thinks, in two stages, as illustrated by Figures 18 and 19. In the first stage, the fractures of the Frisco and Transvaal sets were opened as a system of two sets of conjugate shear fractures in response to a tensional stress directed nearly horizontally at right angles to their strike combined with a compressive stress directed nearly vertically. In the second stage the fractures of the Cobriza and Footwall sets were opened as a second system of two sets of conjugate shear fractures in response to a tensional stress directed somewhat similarly to the tensional stress of stage one but plunging downward to the east, in fact in a direction about normal to the attitude of the Transvaal vein set, combined with a compressive stress directed more nearly horizontally than vertically. These fractures of the second stage have a two-fold importance. Not only were they available for ore deposition, but of even greater significance, the forces which opened them also reopened the earlier formed fractures of the Frisco and Transvaal sets and so made the whole block of ground now occupied by the Frisco mine an especially favorable place for ore deposition.

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of the Footwall and Cobriza sets) of the second stage of deformation and the orientation of the greatest (P_2) and the least (R_2) principal stress axes; each lies nearly in a vertical plane, P_2 striking north-south, and R_2 striking east-west. In each stage, the intermediate principal stress axis (Q_1 or Q_2) is, of course, the line of intersection of the fractures.

The proposed scheme of deformation can be tested in several ways, which are taken up below. First, the relative ages of the fractures and the directions of movement on the fractures during each stage must be consistent with the proposed scheme. Moreover, the stresses of the second stage should be relieved by movement on fractures of the first stage where they were properly oriented. Finally, the fractures in the main should resemble shear rather than tension fractures and parts that resemble tension fractures should be opened normal to the direction of principal tensional stress.

So far as can be observed, the relative ages of the fractures are those required by the theory, that is, the fractures of the Frisco and Transvaal sets are older than those of the Cobriza and Footwall sets. To interpret the evidence, two general cases of vein intersections must be distinguished. In the case where one fissure vein is displaced by another, the vein displaced is either the older, or the veins are essentially contemporaneous if they are conjugate shears. In a second case, where a vein joins or is cut off by another vein without itself continuing past the line of intersection, the vein cut off is either contemporaneous with or later than the vein that cuts it off; it cannot be earlier for that would require the existence of a displaced segment.

In the Frisco mine, the veins of the Footwall set are consistently the veins of the second case, as was stated in the characterization of the set (page 16). But, moreover, they are the same age as the veins of the Cobriza set. Part of the evidence is that in many places a vein of one set changes its attitude to that of the other set, for example the East Madroños vein on level 4 (Fig. 6). As they are the same age as the veins of the Cobriza set, there is good evidence that they cannot be the same age as veins of both the Frisco and Transvaal sets because the geometrical orientation precludes all four sets from having formed through a single stage of deformation. Therefore, the final conclusion is that the veins of the Cobriza and Footwall sets formed at the same time and later than the veins of the Frisco and Transvaal sets.

Additional evidence that the veins fall into two systems of conjugate shears comes from the location of the veins. Viewed in longitudinal section, the major veins of the Frisco and Transvaal sets are complementary in that at a single place the veins of one set, but not both, are well developed. Thus, in the northern part of the mine, veins of the Frisco set (the Frisco and East Footwall veins) are the strong members of the early-formed system of shears, whereas the East El Mante vein of the Transvaal set is weak. Contrariwise, in the southern part of the mine, the Transvaal vein is the strong member of the early-formed system of shears, whereas the North "H" and South "H" veins are weak. This alternation in strength is to be expected because two sets of conjugate shears rarely develop to the same strength in the same place, as has been widely observed, for example by Turneaure (40). Likewise, at any one place the veins of the Footwall and Cobriza sets are developed unequally strongly.

The rest of the evidence regarding the relative ages of the veins agrees with that just given. Further evidence that the Frisco set is early is that its veins in more places than not are displaced by other veins. Reopening of the veins of the Frisco and Transvaal sets is suggested by the localization of ore

in veins of these sets that lie between the positions of the Cobriza and East Madroños-Auras veins (projected if need be). In the Frisco set, the "AG" vein at the north end of the mine and the South "H," "Q," and Margaritas veins at the south end of the mine are weak, narrow, and carry little or no ore although some of the veins are persistent so that had they been reopened they might have equaled the productive veins of the set (Figs. 2, 7 and Table 1).

Furthermore, the limited available data indicate that the directions of movement on the fractures are those demanded by theory. In the first stage of deformation, the vein fractures moved as normal faults with the net slip nearly parallel to the dip (Figs. 18, 19). In the second stage, the vein fractures of the Cobriza and Footwall sets moved as strike-slip faults with the net slip nearly parallel to the strike (Figs. 18, 19). On the veins of the Cobriza set, the east walls moved southward relative to the west walls, and on the veins of the Footwall set, the west walls moved southward relative to the east walls.

The consequence that the stress of the second stage should be relieved by movement on the fractures of the first stage where they were favorably oriented is clearly met. An outstanding example is the Footwall vein, which is composed of segments of two kinds: generally well-mineralized segments with the attitude of the Footwall set, and generally poorly-mineralized segments with the attitude of the older Transvaal set (Figs. 7, 11). During the second stage of deformation, movement took place shearing and displacing an incipient Footwall vein fracture with the attitude of the Transvaal set, the later, well-mineralized segments of the vein thus have the attitude of the Footwall rather than the Transvaal set, with the original incipient vein fracture remaining only as connecting links, which in most places are poorly mineralized. This and other examples not considered here indicate that veins of the Transvaal set, especially the Transvaal vein, the incipient Footwall vein fracture, and probably the East El Mante vein, were favorably oriented to relieve some of the stress in the second stage of deformation. On the other hand, the veins of the Frisco set were oriented too differently from those of the later sets to allow them to move as shears in the second stage of deformation and accordingly they were instead opened wider (Figs. 18, 19). This reopening and their favorable attitudes at nearly right angles to the shale bedding account for their width and strength.

The remaining consequence of the proposed scheme of deformation that may be tested in the mine is that the fractures in the main are shear rather than tension fractures, whereas local parts of veins that are tension fractures are normal to the theoretical direction of least principal stress. This consequence is well met, for the vein fractures are like both artificial shear fractures and natural fractures that have been interpreted as shear fractures (4; 5; 7, especially p. 147; 19, p. 72; 20, p. 298; 22, p. 104). The descriptions of veins and their photographs, Figures 12 and 17, help to make this clear. But local parts of the veins of the early formed sets (Figs. 13, 16) have some characteristics of tension fractures, because these veins were in part reopened by tensional stress in the second stage of deformation. Where both tension and

shear portions of a vein can be recognized, the best ore is always associated with the tension portions, whether the ore is a replacement or an open space filling.

Of course it would be desirable to know the nature and directions of the forces that determined the stress responsible for the fractures. The information would be interesting in its own right and also would add confidence to the theory and point to new places for exploration. Unfortunately, though, the forces cannot be specified at present because the regional geology is not well enough known. The shears of the first stage are so widespread in the Parral district that they must have required regional rather than merely local forces, but the second formed set of shears are locally distributed and so may have been induced by local forces.

Process of Vein Filling

The veins of the Frisco mine were probably filled in the following way. During the second stage of vein formation, the fractures of the first stage were reopened and those of the second stage opened to allow the passage of a hydrothermal fluid containing fluorine, gold, silver, lead, copper, zinc, iron, magnesium, sulfur, and perhaps other constituents. Silicate skarn minerals were formed from the constituents of the shale, with the addition of iron and magnesium from the fluid; quartz and calcite were recrystallized; fluorite and sulfide minerals were deposited.

Several lines of evidence suggest that the bulk of the mineral matter was introduced together during the second stage of vein formation. First, the uniformity in mineralogy and internal structure of the veins and wall rocks suggests that all the veins were filled in the same way. Although the proportions vary, the mineral species are the same everywhere and the silicate minerals are zoned outward from the vein centers implying that the minerals were formed as the result of one process, with their proportions depending on the length of time a vein fracture was open, the physical conditions, and the volume of the fluid that was passed through. Next, the minerals were deposited in a complementary way; that is, as explained earlier, the oreshoots of neighboring veins, particularly those of the same set, do not overlap as seen in longitudinal section. This is because the vein fractures were opened and filled at one time to relieve one stress condition; if they had been opened and filled at different times, gaps and overlaps would be expected in the longitudinal projection of the oreshoots (Fig. 15). Finally, the mineral matter is delicately localized by the portions of the veins opened by shear or tension, suggesting that ore deposition accompanied fracturing.

When a fracture first opened, the walls and fragments of shale within the fracture were silicified and silicated. The common silicate minerals—diopside, actinolite, ilvaite, and epidote—are all complex silicates principally of calcium, iron, and magnesium. Epidote is found throughout the mine, both near the veins and in the walls, and represents the weakest recognized degree of silication. With more intense silication, actinolite and diopside appear, with diopside almost entirely confined to the lower levels. The occurrence

of ilvaite is not well known but it is most common on the lower levels and in many places is closely intergrown with diopside. The silicate minerals and much of the quartz formed by replacing shale to form book or ribbon structure, evidently in the manner suggested by McKinstry and Ohle (22). In a general way, silicate minerals are more abundant on the lower levels than above but some veins even at depth contain little or no silicate mineral matter, presumedly because little hydrothermal fluid passed through, whereas some veins on the upper levels are intensely silicated.

The gangue minerals of the Frisco mine are among those characteristic of skarn deposits and are alike or similar to the minerals of the deposits in the following list, which includes skarn and other deposits related by mineralogy.

Santa Barbara, Mexico	(29)	Andover, New Jersey	(34)
Fresnillo, Mexico	(38)	Balmat, New York	(1)
Santa Eulalia, Mexico	(28)	Trepca, Yugoslavia	(8)
Taxco, Mexico	(9)	Central Sweden	(24)
Velardeña, Mexico	(37)	Shasta Co., California	(27)
Hanover, New Mexico	(33)	Capitan, New Mexico	(13)

With few exceptions, these deposits have in common (1) a few species of ore minerals, mostly simple sulfides and iron oxides, (2) quartz, calcite, and fluorite, or fluorine-bearing minerals, (3) a characteristic group of silicate minerals, especially pyroxenes of the diopside-hedenbergite series, amphiboles of the tremolite-actinolite series, epidote, ilvaite, and garnet (andradite in most places).

In some of the deposits, the skarn minerals were formed with the addition of much material; an outstanding example proved by careful work is Hanover, New Mexico (33). Elsewhere, the skarn minerals were evidently formed by contact metamorphism with the addition of little or no material. At Frisco, although the constituents, with the probable exception of fluorine, necessary to form the gangue minerals are all present in the shale it is not known whether they occur in the proper proportions. Most likely, the bulk of the calcium, silicon, and aluminum, and part of the iron and magnesium were derived from the shale, and the rest, together with the fluorine, sulfur, and valuable metals, were introduced from without.

Somewhat later at any particular place in the Frisco mine than the silicification quartz and the silicate minerals, but during the same general epoch, the sulfide minerals were deposited, with many of the grains replacing fragments of intensely altered shale. Some pyrite was present in the shale before ore deposition and part at least of the pyrite in the veins is earlier than the other sulfide minerals, for it is veined and corroded by the other sulfides, especially by chalcopyrite and arsenopyrite. The textures indicate that, aside from the pyrite, the other sulfide minerals are of the same general age, and that the bulk, but not all, of the sulfide mineral matter is later than the gangue mineral matter. As the elements of the sulfide minerals, except for iron and sulfur present as pyrite in the shale before vein filling, are not seen in the shale, the writer believes them to have been introduced, most likely by the same hydrothermal fluids that are believed to have formed the vein minerals.

Some of the quartz and calcite and most of the fluorite appear to have been deposited relatively late. Anhedral crystals of these minerals fill interstices between other minerals and euhedral crystals of them line vugs.

The mineralogy of the veins of the Frisco mine is like that of the veins at Santa Barbara, included by Lindgren (18, p. 694) in his hypothermal class of deposits believed formed at high temperature and pressure. As the filling of the veins of the Frisco mine probably took place at no great distance below the surface, the deposit might be classed as xenothermal, but the mineralogy is not similar to that of the type deposits (2). By following Lindgren's classification, the aim of grouping deposits of like mineralogy is achieved.

Nothing accurate can be said about the pressure at the time of ore deposition. As the shale is but slightly metamorphosed and of Mesozoic age, ore deposition probably took place under relatively slight rock pressure. The temperature of the hydrothermal fluid could have been initially relatively low because before silication the shale contained a mineral assemblage—namely clay minerals, carbonates, and quartz—that becomes unstable with a moderate elevation of temperature. The temperature was doubtless lower than temperatures common in the more intense zones of contact metamorphism where garnet and olivine are formed.

Geologic History

The shale was laid down, probably in Cretaceous time, overlying older, unknown rocks. Evidence outside the district suggests that the shale is one of the younger formations of a thick series of shales and limestones. After deposition the shale was folded.

Later, the shale was fractured in two stages, distinct in orientation of stress but not necessarily separated by any great length of time. In the first stage, two sets of complementary shear fractures were formed. In the second stage, the first two sets of shear fractures were reopened and two additional sets of shear fractures were formed, while, concurrently, hydrothermal fluids passed through the fractures to form the veins. The geologic times of the fracturing, vein formation, and later events in the district are not known.

Next, the rhyolite sills and dikes were intruded. Then, after a period of erosion sufficient to produce a gently rolling surface, the gravel was laid down, to be later eroded from most of the surface together with more of the older rocks.

Then the ground was fractured by faults at right angles to the veins. Although wide and persistent, these faults have throws measured in only a few meters. Diabase dikes were intruded along the faults and presumably fed the basalt flows which covered the entire area, with the probable exception only of the upper portions of the larger rhyolite bodies.

The final event in the history of the area was erosion to the present topography. Topographic evidence indicates that the present valleys correspond to ridges in the pre-basalt topography and were eroded along the crests of shale hills because the basalt cover was thin or lacking. The basalt, rhyolite, gravel, and veins all resist erosion much more than the shale, except near the veins where the shale is silicified.

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First, the writer thanks Mr. H. B. Hanson, General Manager, San Francisco Mines of Mexico, Ltd., for permission to undertake the work and to publish the results. In Mexico, the writer also profited greatly from the advice of Mr. A. B. O'Neel, Assistant General Manager, and Mr. H. G. Dudley, General Superintendent.

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In making these acknowledgments, the writer wishes to state that he alone is responsible for errors and shortcomings.

COLONIA SAN ANTONIO,
SAN FRANCISCO DEL ORO,
CHIHUAHUA, MEXICO,
Oct. 4, 1955

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THE GEOLOGY AND ORE DEPOSITS OF THE QUIRUVILCA DISTRICT, PERU

RICHARD W. LEWIS, JR.

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ABSTRACT

The Quiruvilca copper-lead-zinc district is in the Department of La Libertad in north-central Peru. The only large mine in this area is the Quiruvilca mine, owned and operated by the Northern Peru Mining and Smelting Co. The mine lies in bedded andesitic and basaltic volcanics, which have been intruded by a small plug of andesite. Numerous dikes and breccia pipes cut rocks surrounding the small plug. To the west of the Quiruvilca mine are four dacite plugs enclosed by sandstone, and 7 kilometers to the east slightly metamorphosed Cretaceous sediments crop out.

The ore deposits of the district are mesothermal and epithermal and were formed by fissure filling. Mineralization followed a pre-existing set of tension and shear fractures and the veins form a well-defined oblique grid pattern. Only a few of the many veins in the area are productive. The wider ones, which average a meter in width, are being exploited. On the basis of mineralogy the mineralized area can be divided into four distinct zones. From the center outward these zones are: 1) the Enargite zone, 2) the Transition zone, 3) the Lead-Zinc zone, and 4) the Stibnite zone.

INTRODUCTION

For several years the U. S. Geological Survey, in collaboration with the Geological Institute of Peru, a bureau of the National Institute of Mining Investigation and Development, has been carrying out a systematic appraisal of the lead and zinc resources of northern and central Peru. The work is being done as part of the program of Technical Cooperation (Point IV) under the auspices of the U. S. Department of State. The study of the Quiruvilca mine was planned as part of the general investigation of lead and zinc deposits in the Department of La Libertad, but inasmuch as the area shows an excellent example of hypogene mineral zoning, the study was expanded to include the entire district.

Four months were spent during 1951–1952 in a general reconnaissance of the surface geology and in mapping the Quiruvilca mine. Surface mapping was done on a 1:4,000-scale map provided by the Northern Peru Mining and Smelting Co. The Quiruvilca mine was mapped on 1:500-scale maps furnished by the company, and vein geology was taken from company maps. Over 50 adits and prospects were studied or inspected. Ore samples were collected from all of the stopes and faces in the Quiruvilca mine and from most of the small workings on the surface. More than 120 rock specimens and 130 sulfide samples were collected. From this suite of specimens, 20 polished sections and 60 thin sections were made and studied. All microscopic identification of sulfides were checked by microchemical tests.

I wish to express my gratitude to Guillermo Abele, of the Geological Institute, who assisted me during most of the field work; to Frank S. Simons, of the U. S. Geological Survey for his general assistance and careful editing; and to my colleagues George S. Ericksen and Robert F. Johnson with whom various phases of the work were discussed. Cordial thanks are due the officials of the Northern Peru Mining and Smelting Co. for making this study possible and for providing me with the facilities of their Shorey-Quiruvilca camp. I wish to acknowledge in particular the cooperation and pleasant hospitality of Harvey D. Willeford, former mine superintendent at Quiruvilca. Lawson P. Entwistle, chief geologist of the company, offered many helpful suggestions and ideas about the structure and nature of the ore deposits. Cliff A. Everett, resident geologist, also aided me considerably both in mapping the mine and completing the reconnaissance of the surface geology.

LOCATION AND GENERAL DESCRIPTION

The Quiruvilca copper-lead-zinc district is in the Department of La Libertad in north-central Peru, 80 km east of Trujillo. It may be reached by automobile from Trujillo over 130 km of all-weather road. The district lies in a region of moderate relief, and altitudes range from 3,450 m at the western edge to 4,050 m at the eastern edge. The climate is temperate with a rainy season extending from November until April.

The only large mine in the area is the Quiruvilca copper mine, owned and operated by the Northern Peru Mining and Smelting Co., a subsidiary of the

American Smelting and Refining Co. All other mining operations consist of small-scale exploitation of high-grade lead-zinc and silver-antimony ores.

The Quiruvilca mine consists of about 25 km of workings serviced by the Elvira and Graciela shafts. Less than half the workings are in use, and most of the unused workings are inaccessible because of caving and water. The mine is worked from 11 levels; the lowest is the 220 level, which lies 300 m below the collar of the main (Elvira) shaft. During 1952, mining was carried out along nine semiparallel veins. Copper in the mine water is recovered in a scrap iron precipitation plant at the mouth of the Almirvilca drainage tunnel.

The mine is serviced by a 500 ton flotation mill at Shorey, 5 km to the west. Ore is transported from mine to mill on an aerial tram 2.77 km long with a maximum unsupported span of 1,350 m. Concentrates are shipped over another aerial tram to Samne, the trucking point 40.1 km west of Shorey. A third aerial tram 6.7 km long extends from Quiruvilca to the company's coal mine at Callacuyán.

Although the mine probably has been worked intermittently for more than 150 years, large-scale operations date only from acquisition of the property by the present owners in 1924. The mine has been operated from 1924 to 1931 and from June 1940 to the present time.

During 1951, 121,804 short tons of ore averaging 4.44 percent copper and 3.73 ounces of silver per ton were mined, and 13,951 short tons of concentrate were produced. The Sin Nombre vein yielded about 40,000 tons of ore, the Elvira vein 15,000 tons, and the Morococha vein 23,000 tons. The precipitation plant recovered 389 short tons of cement copper averaging 62.35 percent of copper.

GEOLOGY

The Quiruvilca mine lies in bedded andesitic and basaltic volcanics, which have been intruded by a small andesite plug. The bedded volcanics consist of extensive flows of andesite, andesite flow breccia, irregular and localized basalt flows, and a few beds of tuff and tuffaceous lacustrine sediments. The plug is a mixture of fine- to coarse-grained andesite porphyry. These rocks have been invaded by numerous breccia pipes, dikes and volcanic glass, and dacite dikes.

To the west of Quiruvilca are four plugs of dacite enclosed by tuffaceous sandstone. The dacite and the other volcanic rocks of the district are post-Cretaceous. Quartzites and slates of Cretaceous age crop out 7 km east of Quiruvilca.

Sedimentary Rocks.—The oldest rocks of the area are Lower Cretaceous clastic rocks exposed near Callacuyán, 7 km east of Quiruvilca, where they crop out in a north-trending, asymmetrical anticline and syncline. According to Mr. Victor Benavides (personal communication), three lithologic units here correspond to Lower Cretaceous units described by Stappenbeck (1927) from the southern part of the Department of Cajamarca. At Callacuyán, the lowest unit consists of massive sandstone which corresponds to Stappenbeck's

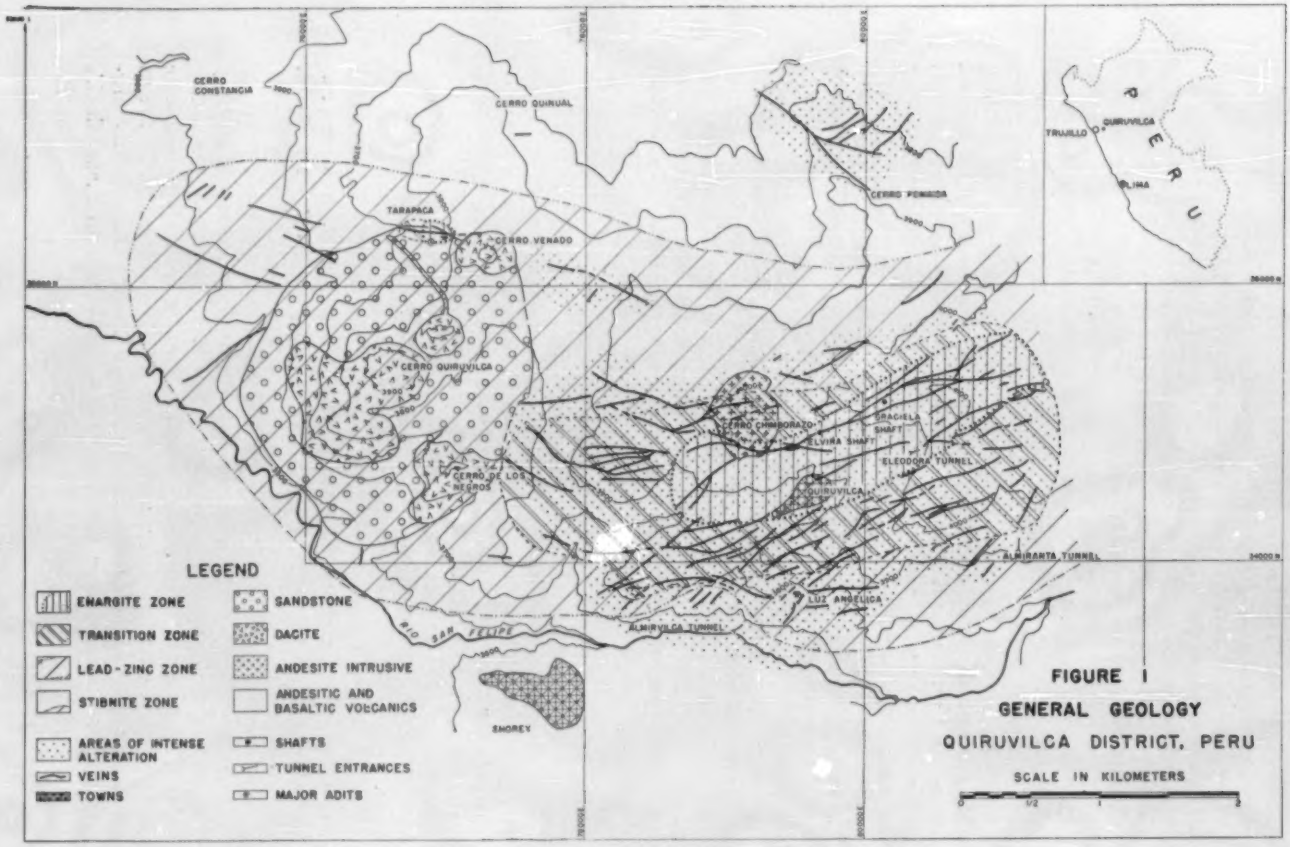

CERRO CONSTANCIA
CERRO QUINUAL
CERRO PENACA
TARAPACA
CERRO VENADO
CERRO QUIRUVILCA
CERRO DE LOS NEGROS
CERRO CHIMBORAZO
SOACIELA SHAFT
ELVIRA SHAFT
ELEODORA TUNNEL
QUIRUVILCA
ALMIRANTA TUNNEL
LUZ ANGELICA
ALMIRVILCA TUNNEL
RIO SAN FELIPE
EMOREY
PERU
TRUJILLO
QUIRUVILCA
LIMA
LEGEND
ENARGITE ZONE
TRANSITION ZONE
LEAD-ZINC ZONE
STIBNITE ZONE
AREAS OF INTENSE ALTERATION
VEINS
TOWNS
SANDSTONE
DACITE
ANDESITE INTRUSIVE
ANDESITIC AND BASALTIC VOLCANICS
SHAFTS
TUNNEL ENTRANCES
MAJOR ADITS
FIGURE 1
GENERAL GEOLOGY
QUIRUVILCA DISTRICT, PERU
SCALE IN KILOMETERS
0
1/2
1
2

FIG. 1.

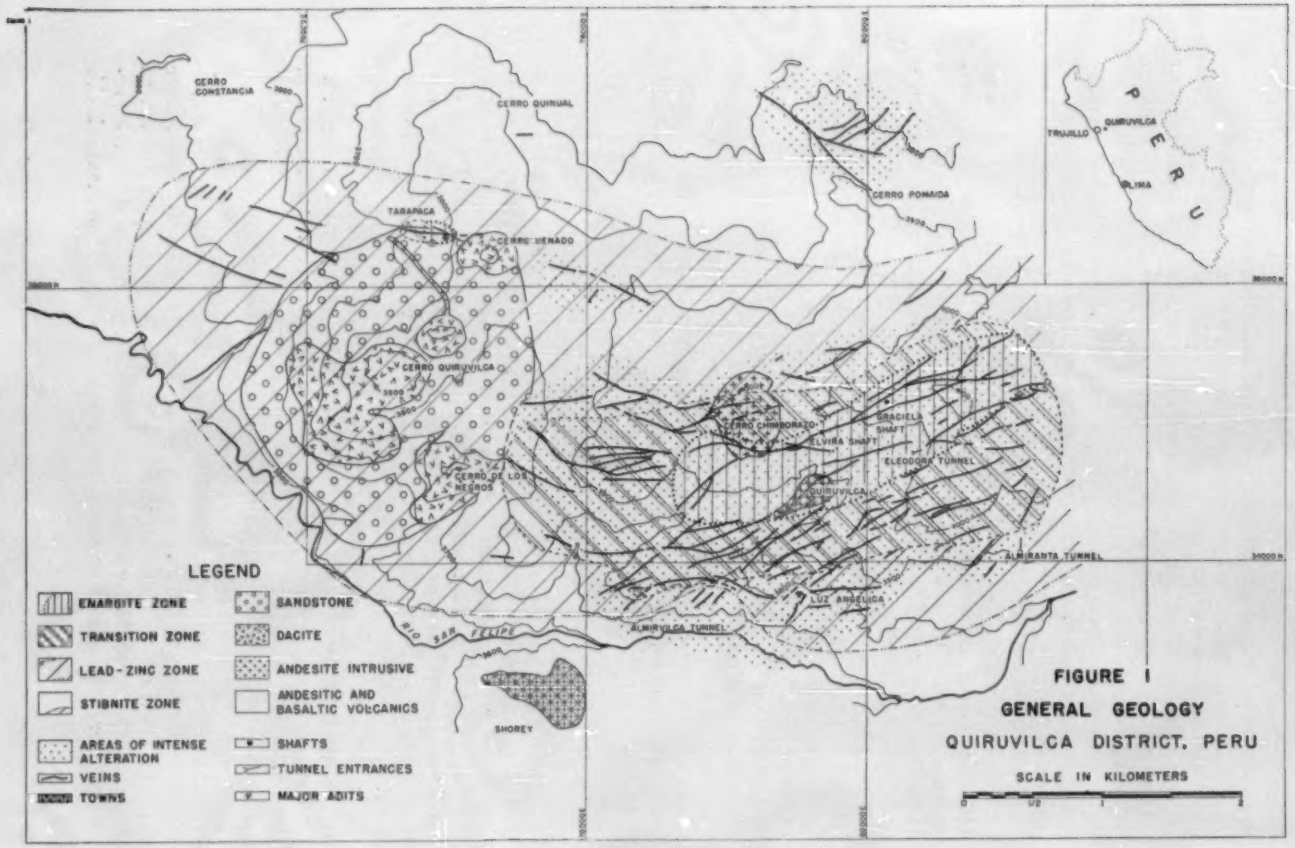
"lower coal-bearing quartzites of the Wealdian"; the middle unit consists of interbedded shales, siltstones, and sandstones equivalent to the Pallares shale; and the uppermost unit is a sandstone equivalent to the Farrat quartzite. Sedimentary rocks of probable Cretaceous age are exposed in a few places in the western part of the area. Contorted black calcareous slate crops out in the east wall of the "explosion crater" northwest of Cerro Venado. Fragments of black shale were noted on many of the small dumps of the abandoned and closed workings on the slope west of Cerro Venado. The shale and calcareous slate are probably equivalent to the Pallares shale found east of Quiruvilca.

The only other sedimentary rocks in the district are the tuffaceous lacustrine sediments encountered in the western and central parts of the area. Most of the sediments are found in the vicinity of Cerro Venado, Cerro Quiruvilca, and Cerro de los Negros and lie in the basin formed by these three hills (Fig. 1). This sandstone is extremely variable in character, grading from a fine-grained tuffaceous sandstone to a pebble conglomerate containing fragments of metamorphic and volcanic rock. Other lacustrine beds were noted northeast, east, and southeast of the town of Quiruvilca, in and amongst the old mine workings. These beds range in thickness from 1 to 10 m and seldom crop out for more than 70 m. These sediments are much finer grained than those found west of Quiruvilca; they consist of mudstones, siltstones, and fine-grained tuffaceous sandstone.

Bedding in some of these lacustrine sediments is well developed but is absent in others. The sorting ranges from very good in the mudstones and siltstones to poor in the pebble conglomerates. The majority of fragments consist of quartz, shale, quartzite, and altered andesite. Minor amounts of magnetite, biotite, chlorite, and oligoclase feldspar were noted. The fine-grained sediments and the matrix of the coarse-grained sediments have been altered to calcite, siderite, clay minerals, and devitrified glass, and all traces of any possible original shard texture have been obliterated. This alteration is particularly intense in sedimentary rocks near the town of Quiruvilca, where these rocks contain pyrite and galena both as disseminations and as 1- to 5-mm seams parallel to the bedding. These sediments are most likely lacustrine deposits of local derivation, deposited in a lake formed by the damming of a stream by lava flows.

Andesitic Rocks.—The predominant rock types of the area are andesite flows and flow breccias, which make up more than 85 percent of the rocks in the area. In the central part of the district the area which contains most of the veins is underlain by interbedded andesite flows and flow breccias. These flows are more or less horizontal and very irregular in form. Interbedded with the andesitic rocks are small basalt flows and a few beds of tuff and lacustrine sediments. No correlation of individual beds has been attempted because of the high degree of alteration and the lack of continuity of the units.

The andesite is dense, blackish green, and megaporphyritic to microporphyritic. In most of the specimens studied all the original minerals except the feldspars, magnetite, and corundum have been altered and the original texture erased. Comparatively fresh specimens show a porphyritic hyalo-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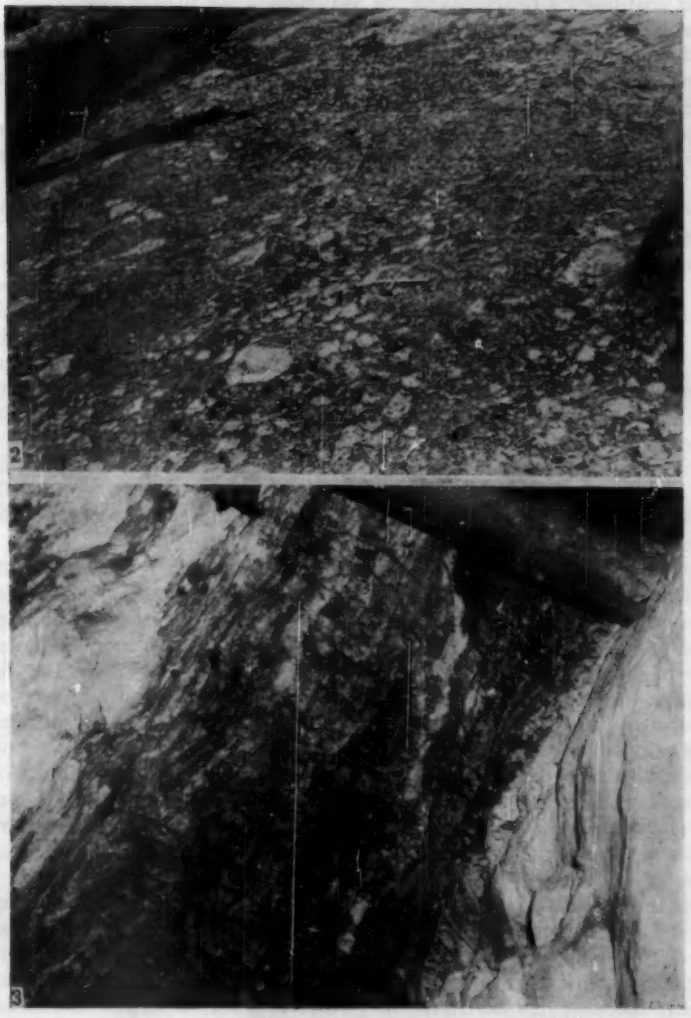

FIG. 2. Weathered surface of an outcrop of the outermost andesite flow breccia. Note the size of the fragments in the background.

FIG. 3. Face of the Sin Nombre vein in a stope below the 50 level. Note the well-developed banding of pyrite (gray) and enargite (black) and the small horses of wallrock (white).

pilitic texture with unoriented phenocrysts set in a groundmass of unoriented feldspar microlites, altered pyroxene, and interstitial glass. The ratio of phenocrysts to groundmass averages 1:1.5. Most of the phenocrysts are slightly zoned plagioclase with an average composition of An_{45}, but larger phenocrysts are zoned from An_{65} in the center to An_{45} at the borders. Some of the completely altered phenocrysts were probably pyroxene. Minor amounts of magnetite, apatite, corundum, and skeleton crystals of ilmenite were noted.

The flow breccias have textures and compositions identical with the andesite flow rock. They consist of fragments of andesite cemented by more andesite of the same or finer grain size. The fragments range from 10 cm to 3 m across, the average size being about 20 cm. The abundance of fragments varies considerably, and for mapping purposes in the mine the breccia was defined as a rock composed of more than 20 percent fragments. A gradation from massive andesite through fractured andesite to breccia with 50 percent or more of fragments often takes place within tens of meters. Gradational contacts and identity of composition and texture indicate that the andesite flows and flow breccias of the central part of the district are contemporaneous.

The extensive flow breccias that surround the central area where most of the veins are located differ slightly in texture and composition from the andesitic rocks of the central area. The matrix is green microporphyritic hyalophitic andesite with feldspar of An_{28-38} composition, and the fragments consist of at least two different types of dark-green to purple megaporphyritic andesites, one containing phenocrysts of composition An_{35-45} and the other phenocrysts of composition An_{55-65}. Textures of the fragments range from trachytic to hyaloophitic and hyalopilitic. The fragments range in size from 1 to 100 cm and compose 60 to 90 percent of the rock. Because of the marked contrast in color between the fragments and matrix, this flow breccia is usually easily recognized in the field (Fig. 2) and possibly could be mapped as a distinct unit. This rock is probably the oldest igneous rock exposed in the area. Its full extent is not known, but it is believed to underlie the surrounding terrain for several kilometers in all directions.

An andesite plug which intrudes the andesitic volcanics of the central area crops out 250 m west of the Elvira shaft. The outcrop is about 500 m in diameter and forms the central part of Cerro Chimborazo (Fig. 1). The rock is a dense, dark-green, megaporphyritic basaltic andesite. The percentage of mafic minerals is higher in this rock, and the feldspars, averaging An_{50}, are slightly more calcic than in the andesite flow rocks.

Basaltic Rocks.—Flows of basalt are interbedded with the andesite flows and flow breccias in the central part of the area. The outcrops range in thickness from 1 to 15 m and seldom are more than 150 m long. The rock consists of two generations of plagioclase feldspar phenocrysts set in a hyalopilitic or intersertal groundmass. The larger phenocrysts have an average composition of An_{60} and are often strongly zoned from An_{80} in the cores to An_{55} at the rims. The later phenocrysts and the groundmass microlites are An_{55-65} in composition. A few phenocrysts of pigeonite and hypersthene are scat-

tered through the rock; the groundmass pyroxene is too altered for positive identification. Minor amounts of magnetite, apatite, corundum, skeleton crystals of ilmenite, and chlorite pseudomorphing an amphibole were noted. These rocks are always less altered than the surrounding andesitic rocks, probably because of selective alteration due to compositional differences. Basalt was cut at depth in several diamond-drill holes north of the Graciela shaft.

Dacite.—Cerros Quiruvilca, Venado, and de los Negros are all composed of a light-gray porphyritic dacite which was intruded in pluglike masses and as series of contiguous parallel dikes. A wall-like dike of dacite extends 225 m northwest from the north side of the northernmost Cerro Quiruvilca plug. The dacite contains inclusions of sandstone and has baked the sandstone along several of the contacts. Within the Quiruvilca mine area several occurrences of dacite porphyry were noted within the mine, especially in the east-central section, as well as on the surface around and to the north of the mouth of the Eleodora Tunnel.

The rock is composed of abundant phenocrysts of oligoclase and a few grains of biotite, quartz, and altered amphibole imbedded in a pilotaxitic groundmass of feldspar microclites, devitrified glass, and iron oxides. The ratio of phenocrysts to groundmass is about 1:1.5. Oligoclase occurs in two generations, an early generation of crystals averaging 1.5 mm in length and An_{27} in composition and a second generation of 0.5 mm crystals with An_{20} composition. Groundmass microlites have a composition of An_{17}. A few of the largest phenocrysts show zoning from An_{44} in the center to An_{27} on the edge; most of them have myrmekitic intergrowths of albite and show evidence of resorbtion.

The principal bodies of dacite found within the mine lie along veins or extensions of vein structures. In addition several vertical northtrending dikes 50 to 200 cm wide were seen. The rock is characterized by subhedral to euhedral quartz crystals and a coarse-grained texture. The quartz grains may be as much as 4 mm in diameter, but average 2 mm. The feldspar phenocrysts are mostly 3 to 4 mm in length. Some fine-grained varieties of dacite were also seen. Alteration of the dacite in the mine has been so intense that the groundmass texture and mafic minerals have been completely obliterated.

A welded dacite tuff crops out at one place on the southern slope of Cerro de los Negros, and a great deal more may be hidden under the alluvium, especially around the bases of the dacite plugs. Several small bodies of tuff were noted in and around the mine, but the high degree of alteration prevented positive identification.

Dikes of Volcanic Glass.—Throughout the mine and at a few places on the surface, small dikes of a green to light-purple aphanitic material were observed. This rock has been so thoroughly altered that it is impossible to say what the original material was. As these dikes fill small and irregular cracks, the original melt must have been highly fluid. This rock was probably an andesite or basalt glass.

Explosion Crater.—About 500 m northwest of Cerro Venado is an explosion crater which was formed during the present erosion cycle. The crater is

350 m long and about 250 m wide. The western side is open and the eastern side is bounded by cliffs of andesite breccia 100 m high. Instead of forming a typical crater the explosion removed a large piece from the side of the hill and scattered debris down the hill for half a kilometer. The depression has an extremely irregular floor and is filled with large blocks of breccia. Although no evidence was found that this youngest volcanic phenomenon ejected any lava or ash, it probably had the same sources as the older volcanic activity. Perhaps late gasses working up along a fracture became concentrated in one spot and caused a minor explosion.

Some Geologic Features of the Quiruvilca Mine.—The majority of the workings of the Quiruvilca mine lie in the interbedded andesite flows and flow breccias. These rocks are particularly well exposed in the eastern and far western sections, where large amounts of flow breccia were seen. Around and to the east of the Elvira shaft lies a large expanse of andesite in which neither breccia nor bedding of any sort was observed. Despite the lack of conclusive evidence, this body seems to be the underground equivalent of the andesite intrusive that crops out on Cerro Chimborazo, east of the Elvira shaft. In the mine this body of andesite is 600 m long and 300 m wide and extends 450 m to the east of the Elvira shaft. Although the alteration of the rocks nearly obscures the contact, the boundaries have been traced from the 50 to the 220 level (Fig. 3). This intrusive appears to be a mixture of fine to coarse-grained andesite. No direct connection between the intrusive and the ore deposits was observed.

Many small breccia pipes and dikes of volcanic glass were noted in the mine. They are mostly in the andesite intrusive near its contact with the bedded volcanics, within the bedded volcanics near the contact between the flows and flow breccias, and in intensely fractured zones. Most of the dikes are less than 5 cm wide, but some are as much as half a meter wide. They are very irregular and seldom extend for more than a few meters. The breccia pipes are irregular and weak; they rarely are more than 10 cm in diameter or more than a few meters long. These pipes consist of altered volcanic glass enclosing fragments of andesite. Larger dikes and breccia pipes are found in the intrusive and the bedded volcanics at some distance from their contact. These dikes average 20 to 40 cm in width and are more or less vertical. The breccia pipes are from 1 to 3 m in diameter and also are nearly vertical. The breccia pipes generally have a matrix of clay or clay and altered volcanic glass with fragments of andesite and, in three examples, numerous fragments of quartzite. A breccia pipe along the footwall of the Number 3 vein on the 50-level contains quartzite fragments as much as half a meter across. On the surface, a small breccia pipe carrying quartzite fragments was noted in the far eastern part of the area. The quartzite fragments are subrounded to well-rounded and were probably derived from sedimentary rocks below the volcanics. Possibly the quartzite is the same age (Cretaceous) as the quartzite found 7 km east of Quiruvilca.

Rock Alteration.—All the volcanic rocks in the district have been altered to some degree, but only in the vein areas has the alteration been intense. Five general types of alteration were recognized; chloritization, propylitization,

propylitization-argillization, argillization, and silicification. Chloritization is the weakest type of alteration and grades into propylitization upon approaching the vein areas. Propylitization-argillization is found in the center of the district around the main vein system; the outer limit of this alteration is the limit of strong alteration shown in Figure 1. The same alteration is also found near isolated veins and vein groups to the north and west of Quiruvilca. Argillization is the highest grade of alteration in the area and is found adjacent to veins or along faults. Silicification, with the exception of the two silicified hills east of Cerro Venado, is closely associated with propylitization and is found only adjacent to veins or vein structures.

Chloritization is shown by some of the basalts and to some extent by the dacite. This type of alteration is characterized by partial alteration of pyroxenes to chlorite-antigorite, the complete alteration of hornblende to iron oxides, devitrification of any glass present, and slight alteration of the larger feldspar phenocrysts to albite, sericite, and kaolin clays.

Propylitization, the common alteration of the basalt flows, is characterized by complete conversion of all mafic minerals to chlorite-antigorite, magnetite, hematite, sphene, leucoxene, and some aragonite. The larger feldspar phenocrysts are partly converted to albite, sericite, epidote, and aragonite. In the groundmass, the feldspar microlites remain unaltered, but the glass and pyroxenes have been converted to quartz, clay, iron oxides, and minor amounts of sphene and leucoxene. Tiny stringers and blotches of epidote and hematite are characteristic. The outermost flow breccias are also strongly propylitized but without the formation of epidote and large amounts of hematite. Commonly the alteration of the feldspars in the breccia is more advanced and in some specimens the breakdown of the feldspar microlites has started.

Propylitization-argillization of the rocks becomes more intense as the veins are approached. In general this alteration constitutes a conversion of all minerals to quartz, kaolin clays, hydromica, aragonite, and varying amounts of chlorite, iron oxides, and introduced silica. Near the outer limits of this alteration the feldspars have not been completely altered and chlorite is still abundant so that the original texture of the groundmass is still recognizable. As alteration becomes more intense antigorite-chlorite and the iron oxides disappear, the feldspars are completely converted to kaolin clays, hydromica, and aragonite, and the original groundmass becomes a mass of clay and quartz. In general, the aragonite occurs only in aragonite-kaolin pseudomorphs after feldspar. Although most of the quartz is residual, some has been introduced. The apparent differences in rock types are mostly due to variation in abundance of the alteration products, particularly aragonite, which accentuates the feldspar phenocrysts, and of iron oxides, which bring about marked color differences.

The rocks near veins and faults are almost completely argillized, and all minerals have been converted to kaolin clays, hydromica, and quartz. Enough of the hydromica is concentrated in pseudomorphs of feldspar phenocrysts to preserve the original porphyritic texture, but the groundmass texture has been completely eradicated. Immediately adjacent to veins and faults argillization

is so intense that the rocks have been completely altered to kaolin clays and hydromica, making the rocks soft and white.

ORE DEPOSITS

The ore deposits of the district are mesothermal to epithermal and were formed by fissure filling. Ore deposition probably closely followed the emplacement of the dacite porphyry dikes and is genetically related to them. Mineralization has followed a set of tension and shear fractures, and the veins form a well-defined oblique grid pattern. The veins in the center of the district are characterized by enargite and are mesothermal deposits. The peripheral veins contain mineral assemblages characteristic of epithermal deposits. On the basis of mineralogy, the mineralized area of about 24 sq km may be divided into four distinct zones. From the center outward these zones are: 1) the Enargite zone, 2) the Transition zone, 3) the Lead-Zinc zone, and 4) the Stibnite zone. In general, the vein material is coarsely crystalline and fairly massive. The veins are locally vuggy, and in many places well-developed banding was seen. Contacts between vein and wall rock are usually sharp and slightly slickensided.

The veins at Quiruvilca form a well-defined oblique grid pattern. One set of veins trends N 60°–70° E and the other N 85° W to S 85° W; most of the veins belong to the N 60°–70° E set. Most of the veins lie along faults which dip at least 70°. Apparently, horizontal movement along a set of east-striking premineral fractures caused the formation of tension or gash fractures striking N 60°–70° E. Several unmineralized east-striking faults were found just north of the Río San Felipe along the southern edge of the vein system, suggesting that the valley of this river may be the site of one of the major east-striking shear zones. Movement took place along a series of small, parallel strike-slip faults.

Most of the sulfides were deposited in fissures of the N 60°–70° E system of gash fractures. The veins of this system are characterized by massive, slightly fractured, banded sulfide ore. Contacts between sulfides and wall-rock are sharp and marked by little gouge. Horses and stringers of wallrock within the vein are common (Fig. 3).

The veins of the east-striking system usually branch out and cut across the veins of the N 60°–70° E system, but in several places a N 60°–70° E vein terminates against an east-striking vein. The fact that many of the east-striking veins cut across the other veins without offset indicates that their formation was probably contemporaneous with the other set. The ore-bearing solutions filling the tension fractures also entered and filled this pre-existing set of shear fractures. Renewed movement along the east-striking shears during later stages of mineral deposition is indicated in the eastern part of the Quiruvilca mine, where the veins of both systems have been broken up into a series of en echelon segments connected by diagonal crossings of ore.

Evidence of post-mineral movement along mineralized and unmineralized shears is abundant within the Quiruvilca mine, particularly in the Morococha vein. The highly friable condition of the ore in this vein and the large

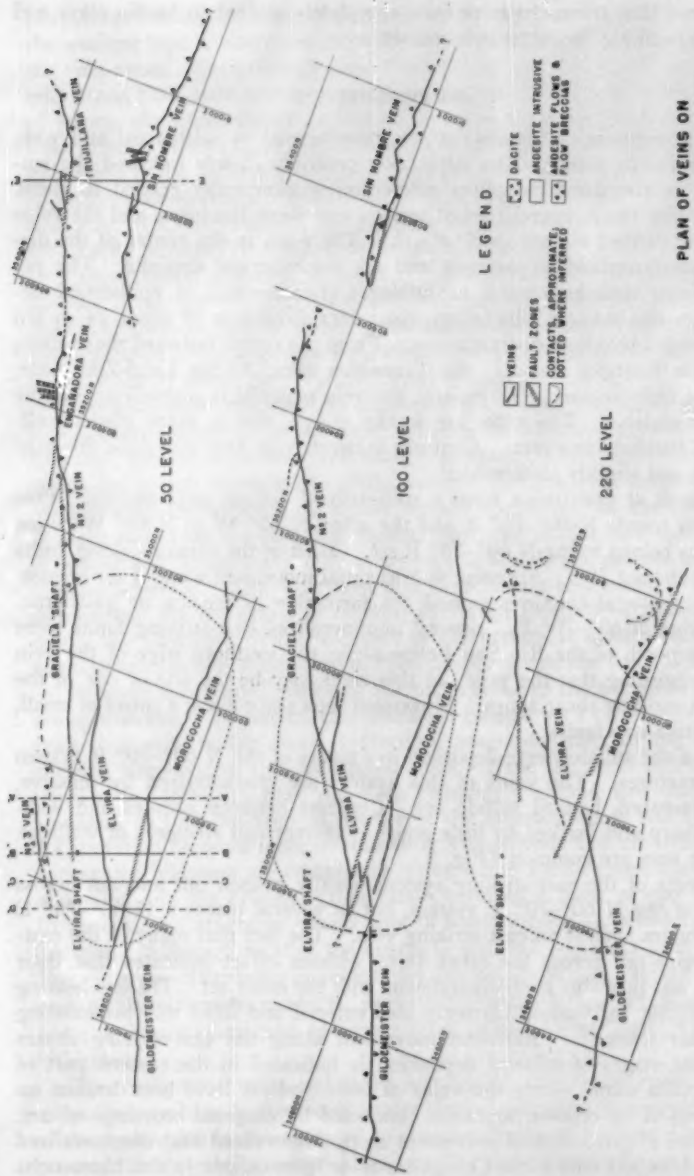

FIG. 4. Plans of 50, 100, and 220 levels showing geology and veins.

amounts of gouge along the walls indicate considerable post-mineral movement. The vein lies in one of the major east-striking shear zones. Post-mineral movement along this zone has cut the Gildemeister-Elvira vein, which occupies one of the N 60°–70° E fractures, and displaced the Elvira vein 60 m to the west (Fig. 4).

The Morococha fault or shear zone is not a simple fracture but a complex series of steeply dipping, semiparallel faults, veins, and breccia and shear zones (Fig. 5). The Morococha vein does not follow consistently the plane of one fault, nor does it have a constant width, strike, or dip but instead has followed several semiparallel faults. Thus, the vein swings, splits, and pinches out as

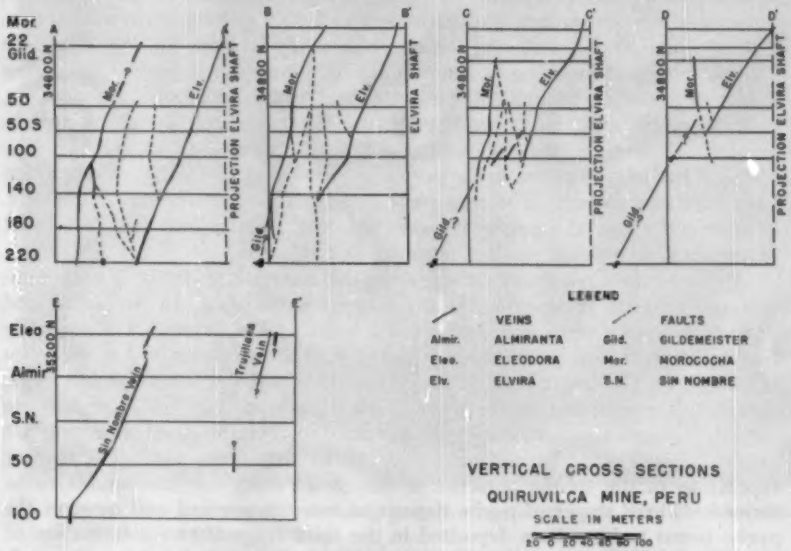

FIG. 5. Cross sections of veins in Quiruvilca mine.

it changes its course from one fault to another. The split in the Morococha vein below the 100 level (Fig. 5, section A-A′) is a typical example of the changes in the vein course. Here the vein switches from one fault to another by means of a diagonal crossing.

ZONING

Enargite Zone.—The Enargite zone is located at Quiruvilca and embraces most of the workings of the Quiruvilca mine. At the surface this zone has the shape of an elongated oval, 2800 m long and 700 m wide. The zone is defined by the presence of enargite. Associated sulfides are pyrite, tetrahedrite-tennantite, wurtzite, sphalerite, chalcopyrite, realgar, and galena. Non-sulfide minerals are quartz, calcite, and gypsum.

The enargite is generally massive and coarsely crystalline; individual crystals average 1 cm in width and 4 cm in length. The development of enargite crystals in many of the vugs is phenomenal; nearly perfect prismatic crystals of enargite as much as 20 cm in length and 5 cm in width have been found. Many clusters of slightly smaller crystals have also been discovered, and large clusters of crystals 1 to 3 cm long are fairly common. The crystals in the smaller clusters are usually coated with small crystals of enargite and pyritohedrons of pyrite. The enargite is remarkably pure and contains only 0.5 percent of impurities. A spectrographic analysis of the enargite made in the Geological Survey laboratory showed XX percent of copper, sulfur, and arsenic; 0.X percent of antimony; 0.0X percent of silver, molybdenum, tin, zinc, cadmium, chromium, and barium; and 0.00X percent of iron, titanium, calcium, manganese, and magnesium. An analysis made by the Northern Peru Mining and Smelting Co. showed 0.5762 percent of impurities, including 0.22 percent of antimony, 0.19 percent of tellurium, and traces of selenium, gold, bismuth, lead, indium and germanium but did not show any molybdenum, cadmium, barium, titanium, calcium, manganese, or magnesium.

Enargite follows pyrite in the sulfide sequence and two stages of deposition have been recognized. The first stage is replaced by tetrahedrite-tennantite. The second stage of enargite replaces the first stage tetrahedrite-tennantite and in turn is replaced by late tetrahedrite-tennantite.

Pyrite is the most abundant sulfide in the Enargite zone. It is both massive and coarsely crystalline; the crystals are as much as 15 cm across and have both pyritohedral and dipyramidal habits. The crystals are generally coarser at depth and are commonly coated with an iridescent red to blue film of enargite. The larger crystals commonly show well-developed growth rings, indicating the pulsating nature of the pyrite deposition (Fig. 6). Large pyrite crystals in vugs are commonly coated with tiny crystals of enargite and late pyrite. Pyrite was the earliest sulfide to be deposited and in subsequent repetitions of the sulfide sequence it was in all cases the first sulfide to be formed. Three stages of pyrite deposition were recognized and most of the pyrite seems to have been deposited in the third stage after the formation of most other sulfides. Much of the early pyrite has been replaced by other sulfides, especially enargite and tetrahedrite-tennantite, and the remaining crystals show pitted surfaces and corroded edges suggesting that they have been partly dissolved by circulating solutions. Late pyrite replaces the other sulfides and commonly forms large massive bands in the veins. Small crystals of pyrite are disseminated throughout most of the rocks in the zone, but only in small amounts. Whereas the vein pyrite always has a pyritohedral or dipyramidal habit, the disseminated pyrite is always cubic. Sheets of secondary pyrite and calcite 1 to 2 cm thick coat the walls of some of the older workings.

Tetrahedrite-tennantite occurs throughout the Enargite zone but appears to be more abundant in the eastern veins. Two stages of deposition have been recognized (Fig. 7). Early tetrahedrite-tennantite replaces enargite, forming either myrmekitic-like intergrowths of the two minerals or pseudomorphs after enargite (Figs. 8, 9). Late tetrahedrite-tennantite is found in veinlets in the enargite and pyrite. These veinlets are generally concentrated

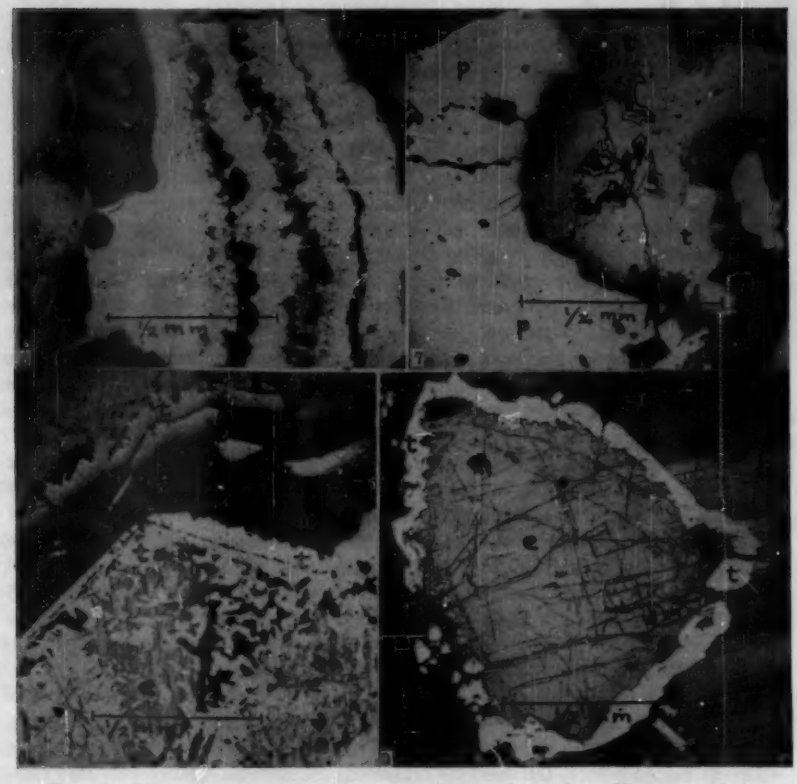

FIG. 6. Microphotograph showing growth rings in pyrite. Note corroded condition of contacts between bands.

FIG. 7. Two generations of tetrahedrite-tennantite (t) deposition, late stage deposited in solution pits in early stage tetrahedrite-tennantite. Pyrite (p).

FIG. 8. Tetrahedrite-tennantite (t) pseudomorphing enargite (e) and replacing it in myrmekitic-like intergrowths. Note second generation of tetrahedrite lining cavity. Section stained with KCN.

FIG. 9. Enargite (e) partly replaced by tetrahedrite-tennantite (t). Section stained with KCN.

near the center of the veins and are more common near the outer edge of the enargite zone.

Wurtzite is the usual form of zinc sulfide in the Enargite zone. It has a distinctive honey-orange color and is found in small stringers near the vein walls. Only one stage of deposition, following the first stage tetrahedrite-tennantite, was recognized. Marmatitic sphalerite was seen in several places, in all cases associated with late galena and quartz.

Chalcopyrite is found in small amounts throughout the zone. It is invari-

ably present in wurtzite as small rounded blebs, which are commonly aligned in stringers. It also occurs along the contacts of the various copper sulfides with one another and with wurtzite. It was deposited along with and just after the wurtzite.

Galena occurs in very small amounts in the wurtzite and also has been seen in late fractures. The Morococha vein is reported to have carried some galena along the footwall in the upper part of the vein. Galena is associated with sphalerite and quartz in small fractures and encrustations in the outer part of the zone. The galena associated with the wurtzite is an early stage sulfide deposited just after pyrite and largely replaced by other sulfides that followed. Late galena was deposited following the third stage of pyrite and is probably epithermal, contemporaneous with the first stage of galena in the deposits of the outer zones.

Realgar is found in a few places in the central part of the Quiruvilca mine in small stringers associated with disseminated pyrite in the wallrock near the veins. The gangue minerals occur in small amounts in open spaces in the sulfides.

The paragenesis of a typical vein is as follows. Pyrite was the earliest sulfide to be deposited and was followed by galena. These sulfides were nearly completely replaced by enargite. Tetrahedrite-tennantite then partly replaced the enargite. Wurtzite was deposited next and was accompanied by chalcopyrite, which partly replaced the wurtzite as well as the enargite and tetrahedrite-tennantite. A second generation of pyrite was then deposited and subsequently was nearly completely replaced by a second generation of enargite. Tetrahedrite-tennantite again followed the enargite, partly replacing it. A third generation of pyrite was followed by a deposition of quartz, calcite, and rare galena.

The Tarapacá vein is a small outlier of the main Enargite zone that lies a few hundred meters northwest of Cerro Venado. This vein contains enargite with associated pyrite, tetrahedrite-tennantite, sphalerite, alabandite, and rhodochrosite. West of this small enargite center is a zone of tetrahedrite-tennantite and sphalerite, and farther west lies the lead-zinc area of Constancia. Thus, it appears that the Tarapacá area shows in miniature the general zoning found in the district.

Transition Zone.—The Transition zone lies between the Enargite and Lead-Zinc zones. Its boundaries are delineated by the disappearance of enargite on the inside and the appearance of megascopic galena on the outside. In many places the exact boundaries could not be located precisely because of lack of information. The zone is most prominent to the west of the Enargite zone, where it is as much as 1,200 m wide, but it was recognized also to the south and north; it appears to be missing along the eastern edge of the district. The inner boundary of the zone is nearer the center of the Enargite zone on the surface than it is underground, so that the Enargite zone has the shape of a flattened cone. The conical shape of the zone is borne out by the fact that diamond drill holes in the Luz Angelica area show vertical zoning from galena-sphalerite at the surface to copper-pyrite at depth. Although

most of the sulfides occur as massive aggregates, well-developed banding was observed in several places.

Pyrite and sphalerite are the most abundant sulfides. The pyrite is mostly massive and commonly shows well-developed growth rings and bands (Fig. 6). The sphalerite is dense and black and occurs in stringers, bands, and masses in the veins. Wurtzite is not abundant and is restricted to the inner parts of the zone. One stage of wurtzite and at least three of sphalerite have been recognized in this zone. In all cases the zinc sulfide follows tetrahedrite-tennantite in the sulfide deposition sequence. Tetrahedrite-tennantite is the principal copper mineral of the zone, although chalcopyrite was noted in several veins. The tetrahedrite-tennantite generally forms masses and stringers in the veins, but it also occurs interlayered with late-pyrite in colloform aggregates. Chalcopyrite is generally present as tiny blebs in sphalerite, but small masses of the mineral were seen in several places. Galena occurs in small amounts interlayered with late pyrite or associated with sphalerite and quartz in encrustations and veinlets. Marcasite and arsenopyrite were found in several of the larger workings in the zone. Arsenopyrite replaces marcasite and they always occur together associated with covellite. Two generations of marcasite and arsenopyrite were recognized. The first generation consists of a mosaiclike mixture of these minerals replacing pyrite. Second generation marcasite occurs as needles in sphalerite and is coated with late arsenopyrite (Fig. 10). Covellite fills innumerable tiny fractures in sphalerite, giving it an iridescent blue color. The mode of occurrence indicates that the covellite is a secondary mineral, probably derived from tetrahedrite-tennantite. Gangue is more abundant in the Transition zone than in the Enargite zone. Massive quartz is the principal gangue mineral, but small amounts of calcite and rhodochrosite were also noted.

The order of deposition in a typical vein is two sequences of pyrite, galena, tetrahedrite-tennantite, sphalerite, chalcopyrite, quartz, marcasite, and arsenopyrite followed by rhodochrosite and calcite. The number of stages of pyrite and tetrahedrite-tennantite is unknown, but this pair of minerals appears to have been repeated at least three times.

Lead-Zinc Zone.—The Lead-Zinc zone lies outside the Transition zone. Its sulfide minerals include galena, sphalerite, pyrite, chalcopyrite, tetrahedrite-tennantite, marcasite, arsenopyrite, and gratonite (?). The zone is 700 to 1,000 m wide to the north of Quiruvilca, 200 to 1,000 m wide to the south, and over 3,000 m wide to the west. Like the Transition zone, it is missing along the east side of the district. The active mines in the zone are in the Luz Angelica area south of Quiruvilca and the Constancia area to the west.

Marmatitic sphalerite is the only abundant zinc sulfide mineral, but some wurtzite was found near the inner edge of the zone. Galena forms either pods within the sphalerite or minute crystals intimately mixed with it. Pyrite is massive and is commonly found banded with sphalerite. Chalcopyrite in all cases occurs as small blebs and seams in and around sphalerite. Small amounts of tetrahedrite-tennantite were seen in many veins in seams and the interstices of quartz grains. Occurrences of marcasite and arsenopyrite, simi-

lar to those in the Transition zone, were noted in places. Arsenopyrite also occurs in comblike masses of prismatic crystals. Tiny prismatic crystals of gratonite (?) are present throughout the zone in small amounts as drusy coatings in small vugs, in interstices of quartz crystals, or replacing galena.

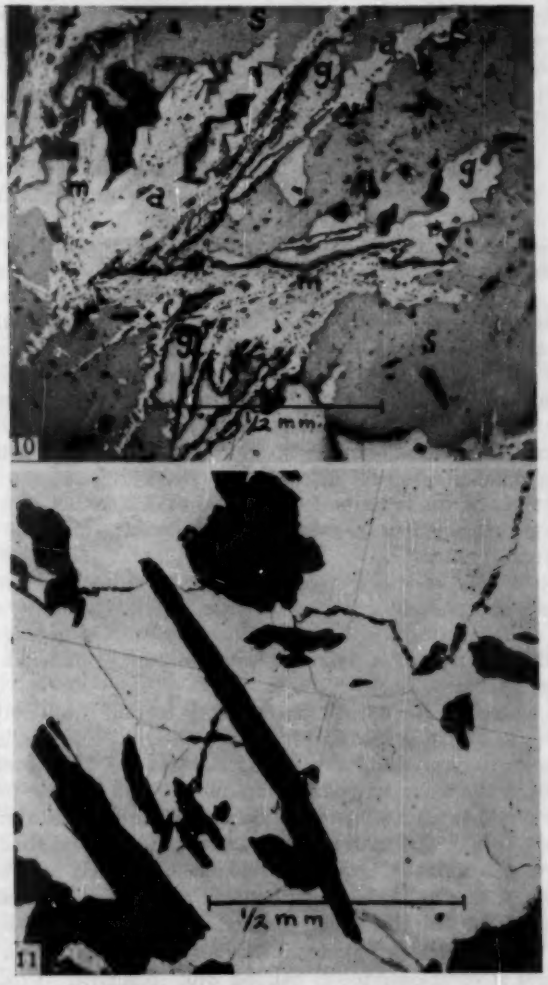

FIG. 10. Needles of marcasite (m) coated with arsenopyrite (a) and cutting across galena (g). Sphalerite (s) has replaced most of galena. Quartz (q).

FIG. 11. Thin section of quartz-stibnite vein. Note second generation stibnite along contacts between quartz grains.

Nonsulfide minerals are quartz, dolomite, rhodochrosite, and calcite. Quartz is abundant and generally occupies cavities. The gossan of many of the veins in this zone carries large amounts of quartz. Dolomite forms prismatic crystals in vugs and thin seams in the veins. Rhodochrosite is restricted to veins near the outer limit of the zone. Calcite is widely distributed, filling cracks and small cavities.

Sulfide deposition can be divided into three distinct stages. The first stage consists of pyrite, galena, tetrahedrite-tennantite, sphalerite, and chalcopyrite in that order. The pyrite-to-chalcopyrite sequence is repeated in the second stage of deposition and is followed by quartz, marcasite, and arsenopyrite. The third stage is a repetition of the pyrite-to-arsenopyrite series and is terminated by gratonite (?), rhodochrosite, and calcite. The first two stages of galena are nearly completely replaced by sphalerite, and the late galena is partly replaced by sphalerite, tetrahedrite-tennantite, and gratonite (?). Pyrite is replaced by sphalerite, marcasite, and arsenopyrite. Early sphalerite and arsenopyrite are replaced by later sphalerite and to a lesser degree by quartz.

Stibnite Zone.—The Stibnite zone, outermost of the four mineral zones, is characterized by the antimony sulfide, stibnite. This zone has been recognized throughout the periphery of the district, except possibly on the east, and is of unknown width. Stibnite first makes its appearance as a component of lead-zinc ores. The galena and sphalerite of these ores are mostly massive, whereas the stibnite shows its typical habit of radiating prismatic crystals. It is also found in masses of acicular crystals set in quartz or carbonate (Fig. 11), or in thin veinlets of fibrous crystals. Two separate stages of stibnite have been recognized, both of which succeed quartz and precede rhodochrosite in the deposition sequence; first generation stibnite may be partly replaced by second generation quartz. Arsenopyrite also appears and is either massive or, more commonly, in bands of short prismatic crystals. Pyrite and minor amounts of tetrahedrite-tennantite and chalcopyrite have been reported. One mine contained large amounts of native arsenic in colloform masses, associated with pyrite, sphalerite, galena, chalcopyrite, and tetrahedrite-tennantite. The nonsulfides consists of quartz and rhodochrosite and may be either banded or massive. Rhodochrosite replaces quartz and was the last major mineral to be deposited. The order of deposition is as follows: pyrite, quartz, tetrahedrite-tennantite, arsenopyrite, stibnite, rhodochrosite, pyrite, tetrahedrite-tennantite, quartz, stibnite, and rhodochrosite. Most of the active small mines and prospects are in the inner part of the Stibnite zone, as the galena-sphalerite-stibnite ores contain large amounts of silver in the form of argentiferous galena and possibly as freibergite.

PARAGENESIS

Paragenesis of minerals has been discussed in the description of the various mineral zones and is summarized in Figure 12. The mesothermal deposits are those of the Enargite zone and part of the Transition zone, and the three outer zones are epithermal in character. Two major pulsations of

ore deposition are recognized in the mesothermal deposits and four pulsations in the epithermal veins.

VEIN DESCRIPTION

Quiruvilca Mine.—Nine different veins were being exploited in the Quiruvilca mine in 1951–1952. The major production was from the Elvira Number 2, Morococha and Morococha Number 2, Trujillana, and Sin Nombre veins. The Gildemeister, Bolognesi, Engañadora, and 477 veins also were being worked.

The Gildemeister vein, the westernmost in the mine, trends N 65° E and has an average dip of 75° S. To the east it terminates against the Morococha vein, and it narrows to the west although the end has not been reached. Workings on the vein extend over 250 m down dip and 400 m along the strike. Most of the ore has been extracted, and only one stope was active

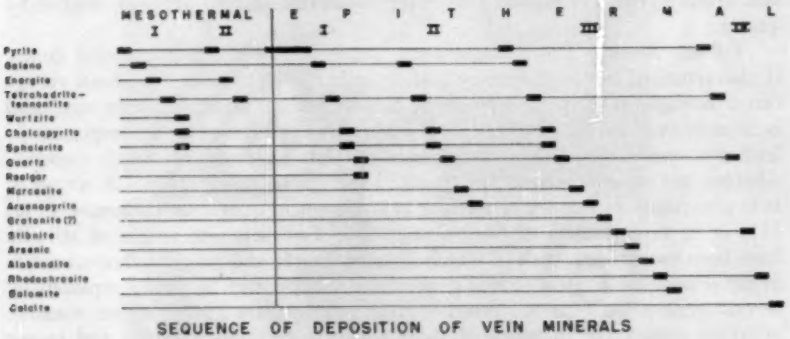

FIG. 12. Sequence of deposition of vein minerals.

during 1951–1952. The vein is reported to have been between 1 and 1.5 m wide throughout most of its extent. Although the vein width increases on the deeper levels, the percentage of copper decreases; on the 220 level the vein is 2 to 2.5 m wide but is almost entirely pyrite. The vein consists of alternating stringers of pyrite and enargite, ranging from 3 to 20 cm in width. The sulfides are massive, containing only a few vugs, and are only slightly fractured. The vein contacts are sharp and marked by only a few centimeters of gouge. Small stringers of late pyrite are found in the wallrock in the immediate vicinity of the vein.

The Elvira vein is actually a faulted segment of the Gildemeister vein. It is offset to the northwest of the east end of the Gildemeister vein (Fig. 4, 5), and has the same attitude and appearance. The Elvira vein segment is about 550 m long and has been worked for 275 m vertically. It has an average width of 1.4 m. The upper levels of this vein were the richest in the mine. In character the Elvira segment is similar to the Gildemeister, having massive slightly fractured ore with sharp and only slightly slickensided

vein walls. It differs from the Gildemeister in having more vugs, small horses of wallrock within the vein, and wider bands of sulfides. The average sulfide band is 10 cm wide, but a 1- to 3-m band of massive pyrite is found on the footwall on the lower levels.

The Morococha vein, which intersects the Gildemeister and Elvira veins at an angle of 20°, trends N 85° W and has an average dip of 70° S from the 22 level to the 100 level; below the 100 level the dip changes to nearly vertical. This vein has been worked for more than 350 m laterally and 330 m vertically. Most of the workings lie to the east of the Gildemeister vein. The Morococha vein averages 1.10 m in width and is distinctive in appearance. Contacts have as much as 20 cm of gouge and the ore is extremely friable. Vugs and horses of wallrock are missing, but banding is well developed. The bands average 15 cm in width and are commonly separated by stringers of gouge. To the east, away from the Gildemeister-Elvira-Morococha juncture, the ore becomes less friable. The vein does not have a constant dip but appears in sections as a series of steps (Fig. 5). Apparently the thicker parts of the vein were the vertical segments, indicating that the hangingwall has moved down with respect to the footwall. Changes in dip and strike indicate that the vein follows no single structure but instead a series of semiparallel mineralized faults connected by diagonal crossings of ore. The so-called Morococha number 2 vein, which strikes N 82° E and is nearly vertical throughout most of its extent, is actually the southernmost of these mineralized faults. The Morococha Number 2 vein is considered here as the lower eastern part of the Morococha vein, even though the principal Morococha structure is mineralized for several tens of meters beyond where the vein splits and crosses over to the Morococha number 2 structure.

The Number 2 vein in 30 m north of the Elvira vein. It has the same strike and dip as the Elvira vein, N 65° E and 75° S, and is connected to the Elvira vein by a diagonal crossing whose intersection with that vein plunges 70° S. The average vein width is 1.10 m. As the 220 level is approached the width increases to an average of 1.15 m but the values decrease. Contacts between vein and wallrock are sharp and slightly slickensided. Sulfides are fractured and pyrite is commonly coated with an iridescent film of enargite; on the lower levels this film is so widely distributed throughout the pyrite that several stopes had to be closed down because of difficulties in concentrating this ore. Enargite commonly occurs in well-developed crystals and tends to be concentrated near the hanging wall on the lower levels of the vein. Banding is evident but ordinarily only three to six bands are present. Horses of wallrock are missing and the bands are not separated by seams of gouge. At the eastern end of the Number 2 vein the Engañadora vein splits off to the south. The Engañadora vein has an average width of 0.90 m. The Number 2 vein dies out a short distance to the east of the split, but its structure continues eastward and becomes the Trujillana vein.

The Trujillana vein is actually a series of en echelon veins which are often connected by very lean stringers. It strikes N 65° E and dips 67° S. The average width is 0.70 m. Workings on the vein extend from near the surface down to the 50 level. The vein is strongly banded and contains small

horses of wallrock and thin stringers of gouge. Vein walls are highly sheared but the ore is not notably fractured. Near the surface tetrahedrite-tennantite is most abundant copper sulfide but on the lower levels enargite predominates.

The Sin Nombre vein, which was the principal producer during 1951–1952, is in the eastern section of the mine, south of the Number 2 and Engañadora veins. It strikes approximately east and dips 75° S. The width averages 1.15 m. The vein has been worked for 400 m laterally and from the surface to the 100 level. In the high-grade sections the vein is massive and well banded but contains many slices of wallrock and seams of gouge (Fig. 3). In the leaner sections wallrock in the vein is so abundant that the vein is reduced to a group of parallel stringers. The vein contacts are sharp and highly slickensided, often having 10 to 15 cm of gouge. The ore is quite friable and locally the sulfides are vuggy. The vein is actually made up of a series of en echelon veins, which trend N 85° W, connected by diagonal crossings that strike N 45° W. On the Eleodora level, three major segments of this vein are completely separated and have accordingly been named the Sin Nombre, Ojos Negros, and Bolognesi veins. On lower levels these segments are joined into one vein, herein considered the Sin Nombre, but the structures of the segments can be traced through all of the levels. En echelon structure in a vertical plane has also been noted in this vein. Overlapping of the en echelon segments is practically nonexistent in both the hoziontal and vertical planes. The main vein segments commonly change strike and the majority of ore is concentrated where these segments change strike slightly just before making a diagonal crossing. These concentrations form actual ore shoots that can be traced from level to level. Individual sulfide bands and stringers average 5 cm in width. The only persistent occurrence of wurtzite in the Quiruvilca mine is in this vein; the wurtzite forms 2- to 5-cm stringers near both the footwall and hangingwall. Tetrahedrite-tennantite also occurs in small bands, which tend to be concentrated near the center of the vein.

About 40 m north of the Number 2-Engañadora split is the 477 vein, which strikes N 80° E and dips 70° N. It has been worked for 160 m laterally on the Eleodora, Sub-Eleodora and, 22 levels. The vein averages 0.85 m in width. It consists of alternating stringers of pyrite and enargite about 5 cm wide. Locally the vein is vuggy. In many places disseminated sulfides and numerous small and localized splits make the vein-wallrock contact very vague.

Other Veins.—The veins of the Transition and Lead-Zinc zones can be divided into three major groups: 1) veins whose dominant mineral is pyrite, 2) veins whose dominant minerals are metallic sulfides other than pyrite, and 3) veins whose dominant minerals are nonsulfides. In general all of these veins have well-defined contacts and slightly slickensided walls. The average width is about 0.75 m.

In the Transition zone the pyritic veins of the first group predominate. In these veins the pyrite is generally massive and locally vuggy, and banding is essentially absent. The other sulfides are either disseminated through the pyrite or found as aggregates within it; these sulfides include only marmatitic sphalerite and small amounts of galena and tetrahedrite-tennantite.

The sulfide veins of the second group are found in both zones but are more

common in the Lead-Zinc zone. In the Transition zone the dominant sulfide is marmatitic sphalerite, whereas in the Lead-Zinc zone both sphalerite and galena are abundant. These veins are mostly massive and banding is generally poorly developed. However, several examples of well-developed repetitive banding of sphalerite, pyrite, and galena were seen in veins with complex mineral assemblages.

The veins with predominant gangue minerals are common to both zones. Some veins are brecciated and in all a regular distribution or banding of the sulfides can be distinguished. Quartz is the most abundant gangue mineral and rhodochrosite is second.

The veins in the Stibnite zone are of two types. Veins of one type are composed solely of a mass of intergrown quartz and stibnite crystals, whereas veins of the other type contain large amounts of other sulfides, mainly sphalerite, pyrite, tetrahedrite, galena, and arsenopyrite, and show evidence of brecciation. Most veins of the latter type contain considerable quartz and a few contain rhodochrosite.

U. S. Geological Survey,
c/o American Embassy,
Lima, Peru,
July 26, 1955

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A METHOD FOR THE DETERMINATION OF ALPHA-RADIOACTIVITY IN PLANTS AS A TOOL FOR URANIUM PROSPECTING[1,2]

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ABSTRACT

Scintillation alpha counting has been adapted to the determination of the radioactivity of plant ash for use in uranium prospecting. A system of sample mounting is described which has high sensitivity and good reproducibility. Background for the system is only 6 counts per hour. The method is sufficiently sensitive so that species which accumulate more than 10 ppm uranium in the plant ash can be used for survey studies.

INTRODUCTION

A NUMBER of surveys have demonstrated the usefulness of plant analyses in the study of certain mineral deposits. Such studies of uranium deposits have been in progress for several years, and the plant analyses have generally been made by the fluorimetric method (Grimaldi et al., 2). This method may be used to determine very small amounts of uranium, but it is costly and requires skilled personnel.

The present paper describes an alpha scintillation method for the analysis of plants for uranium. This method is similar to the one used previously (Anderson and Kurtz, 1), but the sensitivity has been increased about five-fold. The equipment necessary is relatively inexpensive and simple to operate, and the method is sufficiently sensitive for use in the study of uranium deposits provided a suitable type of vegetation is growing over the deposit.

Although the method does not distinguish between uranium and thorium, its application to the survey of thorium deposits has not been investigated.

METHOD AND EQUIPMENT

The alpha scintillation method is based upon the measurement of the rate of emission of alpha particles from plant ash. For this purpose an R.C.A. No. 5819 photomultiplier tube (mounted in a P-12 alpha scintillation detector, Tracerlab Inc., Boston, Mass.) is placed over a silver-activated zinc sulfide phosphor (Fig. 1). The phosphor emits light when it intercepts an alpha particle which was emitted by the plant sample, and this light energy is converted to an electrical pulse by the photomultiplier tube. The pulse is then recorded by a scaler. The number of pulses recorded per unit time is therefore a measure of the radioactivity of the sample. Since the system is light

[1] This study was supported by U. S. Atomic Energy Commission Contract No. AT(11-1)-278, Supp. No. 1.

[2] Arizona Agricultural Experiment Station Tech. Paper No. 374.

sensitive, the entire unit, except the scaler, must be mounted in a dark chamber.

The zinc sulfide phosphor is prepared by coating one side of a $4 \times 4 \times 1/16$ inch leucite plate with a silicone high vacuum grease, dusting the powdered phosphor (obtained from R-C Scientific Instrument Co., Inc., Playa del Rey, California) onto the greased surface, and then tapping off the excess powder. This plate is mounted with the phosphor side down 1.6 cm from the end of the P-12 detector. At this distance the effective counting diameter of the phosphor is 6.5 cm. The design of the sample holder permits maximum counting efficiency and reproducibility.

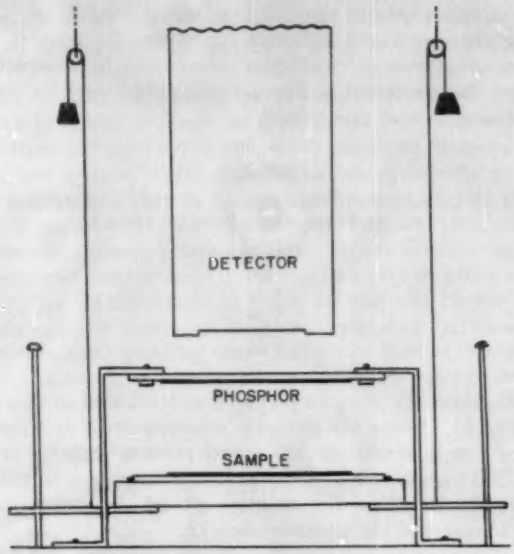

FIG. 1. Alpha scintillation counting apparatus. The detector and sample holder are mounted in a dark chamber provided with a double light trap to permit sample changing.

The samples of plant material are prepared for analysis by washing, drying, grinding (e.g., in a Wiley mill) and incinerating the material in a crucible over a Bunsen burner until a white ash is obtained. The ash is then dusted onto a $4 \times 4 \times 1/16$ inch leucite plate which has previously been uniformly coated on one side with silicone high vacuum grease. The excess material is tapped off the plate so as to leave a uniformly thin source of plant ash.

After a sufficient storage period in the dark (see below), the sample plate is placed on the sample holder and elevated to the counting position 0.5 mm from the phosphor plate. The sample plate is prevented from contacting the phosphor by means of small stops placed around the margin of the phosphor plate. The background count for this geometry is about 6 counts per hour

(cph) at an operating potential of 950 volts. Results are expressed as counts per hour above background. The counting efficiency can be increased by allowing the sample to contact the phosphor, but this necessitates a new phosphor for each analysis and the background count must be estimated or determined for each phosphor plate.

Samples are placed in the dark counting chamber through a double light trap since the phosphor and photomultiplier tube will become activated if they are exposed to light. It was also found that certain plant ashes become activated after prolonged exposure to light and that the counting rate of such samples is almost doubled. Since the luminescence disappears after storage in the dark, all sample plates are stored in the dark for 5 hours. Brief exposure of the sample plates to light of low intensity while transferring them to the counting chamber is not sufficient to activate the samples.

The routine precaution of cleanliness is sufficient to eliminate contamination throughout the procedure. The sample plates may be reused after a thorough scrubbing in soap and water.

TABLE I

EFFECT OF SAMPLE PREPARATION ON THE AMOUNT OF RADIOACTIVITY OF FIVE SAMPLES OF THE SAME PLANT ASH. PROBABLE ERROR 4.3%

Sample	Total counts	cph
A-1	1280	1255
A-2	1280	1164
A-3	1280	1191
A-4	1280	1126
A-5	1280	1145

The probable error for samples prepared and counted as described is 4 to 5 percent (Table I). Since the probable counting error is a function of the total number of counts, a total of 300 counts gives a probable error of about 5 percent, and 500 counts decreases the probable error to 3 percent. In prospecting surveys the length of the counting period depends upon the radioactivity of the sample and the accuracy desired.

EVALUATION OF THE METHOD

Because results of radioactivity determinations are expressed as counts per hour (cph) over background for a sample of standard area and counting geometry, measurement of the weight of plant material or ash is eliminated. The system may be semi-quantitatively standardized by determining the cph per unit amount of uranium in a plant ash of known uranium content.

In order to test the reliability of the alpha scintillation method, and also to determine the range of uranium concentration in which the radioactivity determinations are linearly related to concentration, 10 samples of known uranium content were analyzed. The results show that the activities obtained by the alpha scintillation method closely correspond to the actual uranium concentrations, except when the concentration of uranium in the ash is less than 10 ppm (Table II).

TABLE II

COMPARISON OF THE RADIOACTIVITY OF AN ASH AS DETERMINED BY THE ALPHA SCINTILLATION METHOD WITH THE URANIUM CONCENTRATION AS DETERMINED BY FLUORIMETRIC ANALYSIS [1]

Type of plant	ppm U	cph
Sagebrush	1.7	59
Sagebrush	2.0	60
Sagebrush	4.1	45
Sagebrush	8.5	105
Sagebrush	12.0	118
Sagebrush	21.0	142
Sagebrush	29.0	209
Pinus ponderosa	1.2	56
Pinus ponderosa	1.5	52
Pinus sp. (pinyon)	0.7	60

[1] Samples and fluorimetric analyses provided by Dr. H. W. Lakin, U. S. Geological Survey.

The alpha scintillation method has several limitations. It cannot distinguish between uranium, thorium, or their decay products, but since the type of mineralization present in the soil being surveyed is usually known, this limitation is not serious. The main limitation apparently is the species of plant being analyzed. That is, certain species only slightly absorb uranium from a soil solution which contains a large quantity of dissolved uranium. Thus, the concentration of uranium in the plant ash is quite low and variations in uranium content are masked by the radioactivity of other elements. This may be illustrated by the results in Table II, and also by the analyses of ash obtained from plants of juniper (*Juniperus deppeana*) and mesquite (*Prosopis juliflora* var. *velutina*) growing over a vein-type deposit in southern Arizona. The juniper and mesquite were growing within 10 feet of each other at four locations:

	cph	
Location	Juniper	Mesquite
1	10	28
2	10	270
3	15	222
4	32	500

The alpha scintillation method does not appear to be sufficiently sensitive for the analysis of pinyon pine, juniper, and other species that accumulate small amounts of uranium. Thus the method is limited to the analysis of species of relatively great uranium absorption ability (e.g., *Quercus emory, Q. oblongifolia, Prosopis juliflora* var. *velutina, Mimosa dysocarpa* (Anderson and Kurtz, 1)). The sensitivity of the method could be improved by a number of isolation and concentration methods (Rodden, 3) to permit analysis of plant ash containing less than 10 ppm uranium, but the simplicity of the method would most likely be sacrificed.

The alpha scintillation method was compared (Table III) with radioactivities obtained with a gas flow counter (Model D-47, Nuclear Inst. and Chem. Corp., Chicago, Illinois). This counter does not distinguish between the various types of radiation. Although the counting period could be re-

TABLE III

COMPARISON OF RADIOACTIVITIES DETERMINED ON THE SAME SAMPLE BY BOTH THE ALPHA SCINTILLATION METHOD AND THE D-47 GAS FLOW COUNTER [1]

Results are expressed as cph over background.

	Alpha scint. method cph	Gas flow counter cph
Background	6	1560
Sample 1	445	4400
Sample 2	1125	10140
Sample 3	2535	11940
Sample 3	2535	2160 [2]

[1] We wish to thank Mr. W. Palenscar, Nuclear Inst. and Chem. Corp., for these determinations.

[2] Alpha particles only, determined by difference after removal of alphas with a paper filter.

duced by means of the gas flow counter, this would probably not be advantageous because the presence of K^{40} and other radioactive elements in the plant ash might mask changes in radioactivity due to variations of uranium concentration. However, this limitation could be eliminated by means of proportional counting of only alpha rays.

CONCLUSIONS

Analysis of plant ash for uranium prospecting surveys by means of determining the rate of alpha particle emission appears to be practical for many, but not all, species of plants. The method is applicable to plants that accumulate uranium in excess of 10 ppm in the plant ash.

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Oct. 5, 1955

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HYDROTHERMAL LEACHING IN CENTRAL PERU[1]

W. C. LACY AND H. L. HOSMER

ABSTRACT

Hydrothermal leaching of barite, sulfides and carbonates as a late phase of the mineralization episode is described from several mining districts in Central Peru. Leaching is normally associated with lead-zinc ores and, at Cerro de Pasco, shows a close relationship to pipes of late silver mineralization. The intensity of leaching varies from incipient attack of barite along fractures, in the initial stages, to formation of large open caves with or without collapse breccia filling, in the final stage.

That leaching is a hydrothermal phenomenon is indicated by spatial relationships and by post-leaching deposition of normal hydrothermal sulfides and sulfosalts.

The general sequence of leaching appears to be: (1) removal of barite; (2) leaching of sulfides in the approximate order, tetrahedrite, galena-sphalerite, pyrite, chalcopyrite; (3) leaching of carbonates; (4) deposition of sulfides and sulfosalts.

A tentative hypothesis of origin attributes the change from deposition to dissolution to be related to a decrease in temperature causing changes in the chemistry of the hydrothermal solutions during the end-phases of the mineralizing episode.

INTRODUCTION

A FEW years ago the writers' attentions were drawn to a puzzling phenomenon in Central Peru where the down-dip extension of a well-mineralized lead-zinc vein had been leached of most of its sulfide and gangue mineral components and later sulfides had been deposited upon the residual boxwork. Since that initial observation numerous other similarly leached sulfide bodies have been noted in all stages of the process, from incipient leaching of the mineral components whose effects could be observed only with the aid of a hand lens, to complete leaching of the sulfide and susceptible gangue minerals with resulting open spaces or with collapsed breccia of the hanging wall filling the cavity.

Economically the leaching is of considerable interest in that it appears to be closely related to late silver mineralization, and it must be appraised with respect to ore possibilities above and below the leached zones.

It is more the purpose of this paper to call attention to this feature than attempt to explain it, though a tentative hypothesis of origin is presented. It is hoped that observations will be inspired in other localities and that more field data will be collected.

GEOLOGICAL SETTING

The geology of the mines of Central Peru has most recently been summarized in the *Lead-Zinc Symposium* of the Eighteenth Session of the Inter-

[1] Published with permission of the Cerro de Pasco Corporation.

national Geological Congress (8). The reader is referred to this publication for detailed descriptions of the geology of the region and the various mines.

Along a narrow zone striking north-northwest and straddling, but lying mostly to the east of the continental divide are distributed the many and varied metalliferous deposits of Central Peru. The deposits are generally acrobatholithic, spatially and genetically related to a granodiorite to quartz-monzonite group of intrusive stocks of Tertiary age (5). These have been emplaced into metamorphic phyllites, clastic sediments, limestone, volcanic effusives and explosives, and granular intrusive rocks ranging from Silurian (?) well into Tertiary time. Mineralogy of the ores is notably diversified, from high-intensity oxides and tungstates through low-intensity sulfides and sulfosalts.

Where glacial and stream erosion has been active unaltered hypogene sulfides occur on the surface. However, on the high "Puna" area of gentle relief oxidation effects extend to depths of several hundred feet, and locally to depths in excess of 1,000 feet (6) below surfaces having present elevations of 13,000 to 15,000 feet.

HYDROTHERMAL LEACHING

The writers first became interested in the possibilities of hydrothermal leaching in examining a newly completed low-level tunnel at the Volcan mine at Ticlio, designed to cut the vein structure some thousand feet below the surface outcrop. Instead of encountering the normal three to six foot sulfide vein that had been worked on the upper levels, the tunnel cut a zone of mixed sulfides and leached rubble. A drift along the structure revealed alternating normal sulfide and leached debris. Closer examination of vein material disclosed normal sulfides in quartz-ankerite gangue in which tabular voids had been formed. This graded into material in which galena, sphalerite, and pyrite had been leached, and finally into an open boxwork of residual quartz from which the carbonate had also been removed. There were no evidences of supergene oxidation. Fresh, unetched chalcopyrite crystals were perched upon the surfaces of the boxwork. (Fig. 1.) Along portions of the vein where quartz was less abundant the residual material consisted of fine sandy material or gray to black gouge. The hanging wall diorite in areas of intense leaching had slabbed off, forming a loose collapse breccia.

Search for similar material in other mines in Central Peru has resulted in numerous other observations of identical leaching at Cerro de Pasco, Morocoha, and Casapalca, normally associated with lead-zinc ores. In all instances late deposition of sulfides or sulfosalts upon the leached residue precluded supergene alteration, so a process of hydrothermal leaching seemed to be the most reasonable explanation for the observed phenomena.

The intensity of leaching varies, and the features developed ranged:

(1) Incipient attack of sulfides exposed in vugs and along fractures.
(2) Fissure openings with boxwork or rubble filling.
(3) Pipes with boxwork or rubble filling.
(4) Open caves with or without rubble filling.

Volcan Mine.—The geology of the Volcan mine, located on the continental divide between Casapalca and Morococha, is simple. Mineralization is localized along a single steeply dipping vein system with north-east trend in a quartz-diorite host. The ore contains sphalerite, galena, pyrite and chalcopyrite in a gangue of ankerite, barite and quartz. A late generation of galena, sphalerite, chalcopyrite, tetrahedrite, specularite and ankerite form veinlets cutting the earlier minerals and appear to carry most of the silver values. (Fig. 2.) Silver values are largely confined to the upper levels.

FIG. 1. Quartz boxwork with post-leaching chalcopyrite and pyrite crystals. Barite, sulfide, and carbonate have been removed. From Huacracocha Level, Volcan Mine (× ½).

Leaching was observed to be most abundant on the deepest level of the mine workings, about 1,000 feet below the surface outcrop, and appears to have occurred in the following sequence:

(1) Solution of barite leaving quartz-ankerite-sulfide vein material with tabular voids. Some leaching of sulfides occurred at this time. (Fig. 3.)

(2) Removal of sulfides. It was not possible to determine the order of attack upon the different sulfide minerals. Carbonate was etched and some was removed at this stage.

(3) Solution of carbonate leaving a quartz boxwork where quartz was present in sufficient quantity, or fine quartz rubble, sand, or red, gray, or black gouge where quartz was less abundant.

(4) Deposition of chalcopyrite crystals upon the surfaces of this boxwork. (Fig. 1.)

Hematite and specularite are associated with the leached residue and are believed to represent residual iron from the decomposition and dissolution of pyrite and ankerite.

Where leaching has been extensive the hanging wall of the vein has slabbed,

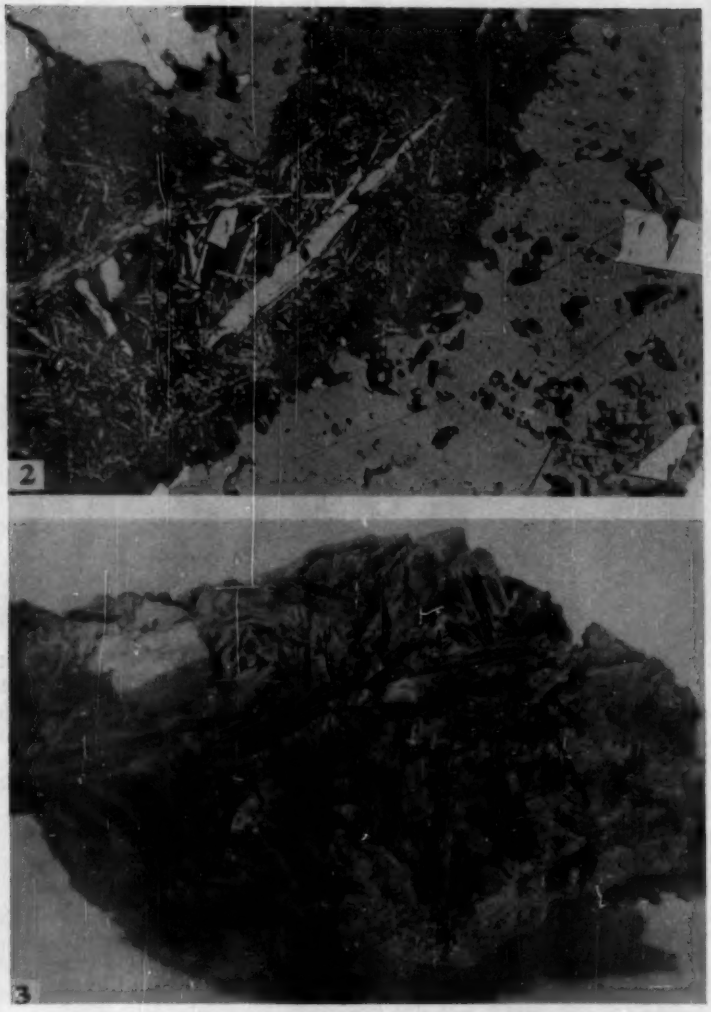

FIG. 2. Late veinlet of specularite and ankerite cutting early sphalerite, pyrite and galena, Volcan Mine (× 130).

FIG. 3. Tabular voids in ankerite resulting from leaching of barite. Late sulfields have been deposited on the surfaces of boxwork. Huacracocha level, Volcan Mine (× 1).

forming a loose-textured collapse breccia on top of the leached rubble and extending along the vein for distances of 10 to 50 feet. These leached areas alternate with sections of normal vein mineralization.

The late veinlets composed of ankerite, specularite, galena, sphalerite, chalcopyrite and tetrahedrite, which appear to carry the silver values, may represent redeposition of materials leached elsewhere from the vein—thus constituting a type of secondary enrichment by hypogene processes.

Casapalca Mine.—Ore mineralization in the Casapalca mine is localized along a fracture system with northeast trend, dipping steeply to the northwest, and cutting Tertiary clastic sediments and volcanic rocks and Cretaceous limestone. A long list of minerals have been identified in the mine but the principal components include sphalerite, galena, tetrahedrite, pyrite, chalcopyrite, and bournonite in quartz, barite, calcite and manganocalcite gangue.

In the upper levels of the mine it is not uncommon to find tabular voids in the quartz-carbonate gangue left by leaching of barite crystals. Recently development work encountered a zone of intense leaching on the 800-foot level of the Bella Union Vein, an eastward split of the Consuelo Vein. The vein material at this location was principally composed of manganocalcite gangue with disseminated sulfides. Leaching was nearly complete leaving only a narrow layer of black, manganese-rich gouge. Some fragile pieces of silica boxwork were preserved. These were coated by a thin veneer of minute pyrite crystals, which began to oxidize upon their removal from the mine. The hanging wall had slabbed forming a collapse breccia on top of the leached debris, similar to that observed in the Volcan Mine. (Fig. 4.)

The sequence of leaching at Casapalca appears to have been:

(1) Removal of barite.

(2) Leaching of sulfides in the approximate order: tetrahedrite, galena-sphalerite, pyrite and chalcopyrite.

(3) Leaching of carbonates.

(4) Deposition of pyrite on residual boxworks. Manganese oxide masks whatever other minerals may be present in the residual material, and it is believed to be residual from dissolution of the manganocalcite.

The "N" split of the Carlos Francisco Vein, developed between the 1,900- and 3,300-foot levels of the mine, exhibits local leaching throughout its exposed vertical extent. Leaching has in general been confined to the vuggy central portion of the banded vein with removal of barite, sulfides, and carbonates. Abundant quartz gangue protected most of the vein from the leaching attack. Where quartz was less abundant leaching was more complete leaving lens-shaped cavities.

No evidence was noted as to redeposition of the leached materials.

Morococha Mine.—Ore mineralization at Morococha is localized along three major loci: (1) as veins along east-west fractures in volcanics, limestone and intrusive rocks; (2) *manto* replacements in favorable limestone beds; and (3) pipes along steep permeable loci such as breccia structures at vein intersections and along intrusive contacts. The central area of the district has been intruded by several stocks and has been profoundly altered.

Progressively outward from the central area the amount of copper in the ores decreases and that of lead-zinc and silver increase.

Hydrothermal leaching effects do not appear to have been intensive in Morococha but they are extensive in the lead-zinc-silver sections of the veins.

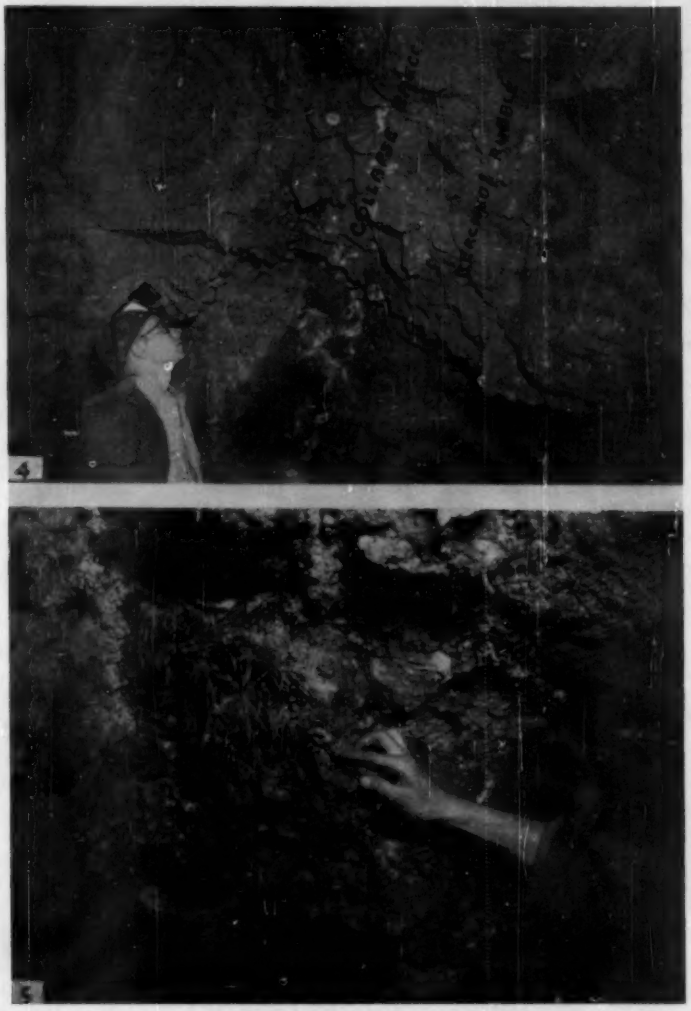

FIG. 4. Collapse breccia forming by subsidence of hanging wall into leached vein. 800 foot level, Casapalca Mine.

FIG. 5. Stalactites of lead-arsenic mineral complex in cave formed by hydrothermal leaching. 1,400-foot level, Cerro de Pasco Mine.

The extent of leaching is normally incipient attack of sulfides along fractures and in vugs producing deeply etched sphalerite and galena crystals with accompanying deposition of minute crystals of pyrite and specularite on etched and corroded surfaces of the ferroan sphalerite. In some places veins are criss-crossed by leached quartz boxwork in small veinlets up to an inch in width. This type of leaching is found from the outcrop down to the 1,700-foot level, the deepest in the mine.

The sequence of leaching is in general the same as that observed at Casapalca:

(1) Removal of barite.

(2) Leaching of sulfides in the approximate order of susceptibility: tetrahedrite, galena-sphalerite, pyrite.

(3) Either simultaneous or later deposition of a pyrite veneer and specularite rosettes on etched surfaces of ferroan sphalerite.

(4) Leaching of ankerite and siderite.

(5) Deposition of pyrite and chalcopyrite crystals on the surface of the residual silica boxwork.

No evidence of a second generation of sulfides related to the leaching was noted.

Morococha offered the one example observed of hydrothermal leaching of enargite. One specimen exhibited leached skeletal enargite crystals up to one inch in length coated with a veneer of minute, late pyrite crystals. Tetrahedrite in this specimen was etched but the early pyrite was unaffected.

Cerro de Pasco Mine.—The orebodies of Cerro de Pasco are localized within and adjacent to a tremendous crescentic mass of pyrite that reaches its maximum size of 6,000 feet long and 1,000 feet wide near the surface and tapers irregularly downward. It has been emplaced along the eastern margin of a large volcanic vent at its intersection with a major fault structure and replaces both the agglomerate filling of the vent and adjacent limestone and shale beds. East-west enargite veins transversely cut the western part of the pyrite mass and continue into the vent rocks. Splaying of the eastern terminations of these veins has in some places resulted in the formation of steep enargite-rich pipes. Lead-zinc orebodies occupy massive pipe to *manto*-like structures, diverging upward, in that portion of the pyrite mass that has to a large extent replaced limestone. In numerous places along the eastern margin of the lead-zinc orebodies and within these orebodies are large voids, commonly filled with collapse breccias of pyrite and sphalerite and crusted with galena, "waxy" sphalerite, pyrite, gratonite, baumhauerite, aramayoite, realgar, hematite, and various complex unidentified mineral species and amorphous materials. These are associated with pipes of late silver mineralization, commencing as deep as the 2,300-foot level and occupying greater areas on consecutively shallower levels.

The leaching processes responsible for the solution were hydrothermal as attested by depth of leaching well below any normal oxidation effects, and the post-leaching deposition of sulfides and sulfosalts.

The lead-zinc minerals were generally more susceptible to the leaching

than the pyrite and the intensity of the leaching varies. It ranges from mere etching with subsequent deposition of hematite, baumhauerite, realgar, along sheeting planes in the sulfide mass, to formation of veinlets up to six inches wide containing leached silica and sulfide boxwork crusted with the late

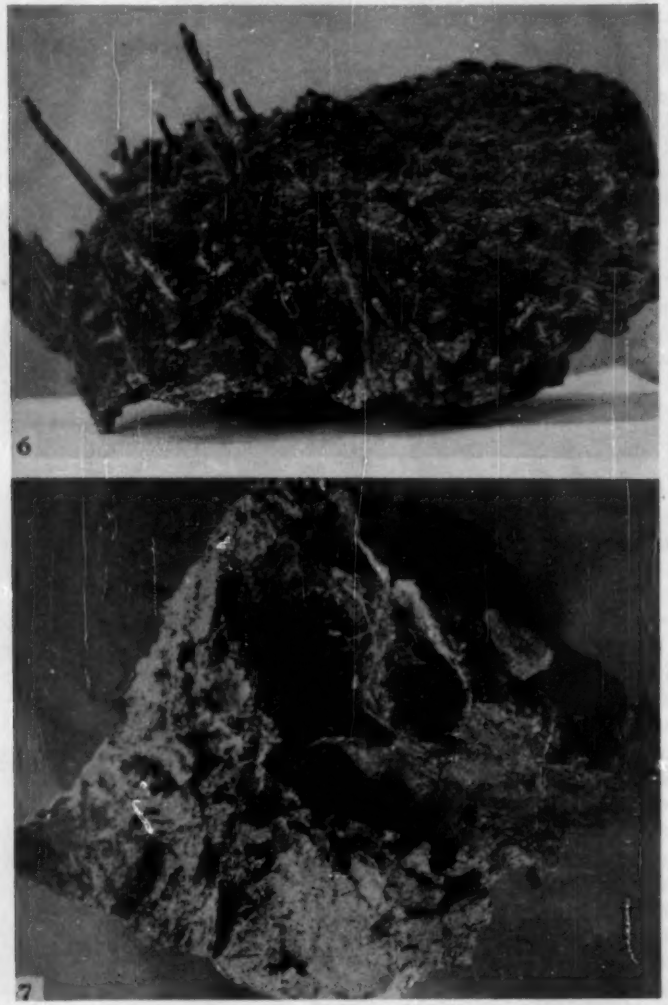

FIG. 6. Tubular stalactites of lead-arsenic mineral complex, 1,400-foot level. Cerro de Pasco Mine (× 1).

FIG. 7. Leached silica boxwork with thin veneer of lead-arsenic mineral complex. 1,400 foot level, Cerro de Pasco Mine (× ½).

mineral complex, or may form caves up to 50 feet in diameter with tabular, elongate or pipe-like forms. These features have been localized along intersecting fractures, intersections of fractures with a zone of brecciation along the footwall of the pyrite mass, and at the intersection of fractures with remnants of sedimentary beds within the pyrite body. In some instances open caves form, others are partially filled with collapsed rubble, or may contain cores of leached, spongey, siliceous material.

The late sulfide complex coating the leached surfaces is, to the writers' knowledge, unique in its mineralogy and occurrence. In places are found euhedrons of gratonite, fibrous masses of aramayoite, crusts of fine grained

FIG. 8. Silica casts of leached carbonate, La Paz 1,000 foot level Morococha Mine.

galena and "waxy" sphalerite, pyrite, realgar, hematite, baumhuerite, a thallium-rich variety of baumhauerite(?), and a complex of amorphous lead-arsenic minerals or glass. Some of this material carries high indium values although no specific indium mineral has been identified.

Within one of the caves on the 1,400-foot level of the mine tubular stalactites of this mineral complex, curved and bifurcating, up to three inches in length, were found hanging from the roof. (Figs. 5, 6, 7.) Crusting botroidal material, consisting essentially of baumhauerite, lined the walls and most of the roof. The floor of the cave was covered with collapsed rubble of mixed sulfide and silica crusted by the late mineral complex and residual clay minerals.

SUMMARY OF OBSERVATIONS

From observations of the phenomenon of hydrothermal leaching in various mines in Central Peru, several generalizations may be made:

(1) Leaching occurs to depths as much as 2,300 feet below the outcrop but is most abundant between 1,600 and 500 feet below the present surface.

(2) Observed leaching occurs late in the sequence of mineral deposition and appears to be related to silver mineralization in time and space.

(3) The leaching is most abundant in lead-zinc bodies and appears to attack the earlier minerals in the following order: barite, tetrahedrite, (enargite?), galena-sphalerite, pyrite, chalcopyrite, carbonates.

(4) Post-leaching mineral deposition may be simple with crystalline pyrite, and/or specularite, and/or chalcopyrite, and/or galena and sphalerite; or it may be exceedingly complex with fine-grained botryoidal and stalactitic forms composed of rare and complex minerals deposited as open space fillings. No replacement phenomena were noted in this late mineral deposition.

HYPOTHESIS OF ORIGIN

The change from deposition of the hydrothermal minerals to dissolution, or hydrothermal leaching, marks a change in the physico-chemical environment. The hydrothermal solutions undergo gradual changes in composition due to changes at their source or reaction with the materials with which they come in contact, and with changing temperature and pressure conditions reactions within the solution itself take place. Since deposition and dissolution are both a function of equilibrium constants, change in ion concentrations might result in precipitation or solution.

Day and Allen (1) proposed the reaction:

$$H_2SO_4 + 3H_2S \xrightarrow{(-200^\circ\ C)} 4H_20 + 4S.$$

Cooling of the ore solutions below approximately 200° C is believed to result in a decrease in concentration of the sulfate ion and an increase in concentration of the bivalent sulfur ion. This would have two effects:

(1) Solution of the sulfate minerals. Barite is one of the last minerals to be deposited and the first to be leached. The equilibrium expression governing the solubility of barite may be written:

$$K_s = \frac{(Ba^{++})(SO_4^{--})}{(BaSO_4)}.$$

Removal of the sulfate ion from solution would result in dissolution of barite.

(2) Solution of sulfide minerals. Hemley (3), in his study of lead sulfide solubility, found that lead solubility as $Pb(HS)_3^-$ complexes and $Pb(HS)$ increases with an increase in bivalent sulfur and decreases with pH values above 7. Changing pH values and increase in concentration of bivalent sulfur ions in the ore solutions may have been the cause of selective sulfide dissolution. The presence of native sulfur beneath the area of leaching and of silver mineralization at Cerro de Pasco (Lacy, 4), is added evidence for such a reaction.

Solubility of carbonates is a function of the concentration of CO_2. Miller (7) states, "As CO_2-pressure increases at constant temperature solubility of $CaCO_3$ increases. On the other hand, at constant CO_2-pressure the solubility of $CaCO_3$ increases with decreasing temperature." Thus, the mere drop in temperature in the hydrothermal solutions might cause deposition of carbonates to change to dissolution.

The late phase mineralization evidenced at Cerro de Pasco featured a dumping of sulfides and sulfosalts with evidence of low temperature fumerolic deposition in the final period of deposition. Graton (2) points out, deposition at any given point in the channelway is on an ascending temperature scale until the crest of the mineralizing episode is reached. This is followed by a "rapid decline in evolution of solutions at the source . . . relatively little takes place along the channelway save cooling down of the deposit."

It is the belief of the writers that the hydrothermal leaching effects which have been observed in Central Peru are the results of this final decline in temperature accompanying the last phases of mineralization.

ACKNOWLEDGMENTS

It is not possible to acknowledge individually the various geologists and miners who have aided in this study by calling attention to examples of the hydrothermal leaching phenomena. However, we are particularly grateful to I. R. Quirke who brought us the first sample of leached material from the Volcan mine which stimulated our interest in the problem, and to F. de las Casas for his help in gathering data on leaching and post-leaching mineral deposition at Cerro de Pasco.

La Oroya, Peru,
September 15, 1955

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GEOLOGY AND THE ORE DEPOSITS OF THE CANTERA MINE, ZACATECAS, MEXICO

JOHN G. STONE

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ABSTRACT

The Cantera mine is one of the few operating mines of the formerly great silver camp of Zacatecas, Mexico. The mine consists of a series of sulphide orebodies along the Cantera Fault, about 5 km east of the city of Zacatecas. The Cantera Fault is a large normal fault striking N70°–80°W and with an average dip of 50°SW. North of the fault, a series of indurated Mesozoic (?) shales or clay slates has been intruded by a small gabbroic stock with associated dikes and sills. South of the fault, the Zacatecas Valley is underlain by a thick sequence of Miocene (?) agglomerates, tuffs, and rhyolites. The volcanism culminated with the eruption of at least 100 meters of rhyolite, presumably blanketing the entire Zacatecas Valley. At La Cantera, this cover has been removed by erosion.

The orebody at La Cantera is an epithermal breccia filling deposit in which there has been considerable replacement. Although mining operations have obscured the vein structure, old reports indicate that the vein consists of two parts—a silver-rich quartz hangingwall vein, and a sulphide footwall vein. A suggested paragenetic sequence for the primary minerals

is: quartz, sphalerite-chalcopyrite, galena, pyrite, quartz, pyrite, calcite. Silver sulphides are presumably present, but their position in the paragenetic sequence is uncertain.

The amount of eluvial silver ore spread over the south slope of the Cerro de la Cantera indicates that 400 meters of vein material have been removed by erosion. The age of the mineralization is not definitely known, but is probably post-Miocene.

The orebody has been broken by later north-south cross-faults with associated quartz veins. Contrary to previous opinion, at La Cantera these cross-faults exercise no control over the distribution of the ore shoots within the Cantera Vein.

INTRODUCTION

Geography. The Cantera mine is one of the few presently operating mines of the formerly great silver camp of Zacatecas, Mexico. The Zacatecas district lies in the midst of a semi-isolated group of hills known as the Serranía de Zacatecas that rise out of the plains in the southwestern portion of the semi-arid Mesa del Norte (8, p. 21) or Mesa Central del Norte (13, p. 1289). The Cantera mine lies 5 km due east of the city of Zacatecas, at an estimated altitude of 2,410 m, (5, map).

The region is one of rounded hills, with a few steep cliffs formed by the thick rhyolites that border the Zacatecas Valley to the south. Along the north side of the valley, the silicified Cantera Fault (Cantera Vein) crops out as a series of prominent ridges, one of which is the Cerro de la Cantera on which the mine is located.

Previous Work in District. The economic possibilities of the Zacatecas district have focused attention on the mining industry and geology of the region ever since its discovery in 1546, so that there is considerable geologic literature on the area. Much of this work was done in the 19th Century, during the most productive years of the district. The first study of the region accompanied by a geologic map was published by Burkart in 1836 (6, p. 1–84). Burkart's detailed descriptions of the various formations in the district and of their relations to one another have provided the base for most later work. In 1886 vom Rath published a short discussion of the geology of the Zacatecas district, including his views on the origin of the "red conglomerate" of Burkart. Burckhardt and Scalia (5) published a short account of the geology of the district, accompanied by a topographic map, as a Guidebook for the Tenth International Geologic Congress. This paper was accompanied by a series of petrographic descriptions by Rosenbusch, and made reference to papers on the Triassic marine fauna of the region. A companion Guidebook described the mining industry of Zacatecas (7). The similarity between the Zacatecas and Guanajuato districts was pointed out by Botsford in 1909. More recently, Bastin (1) has published a paper on the paragenesis of several specimens of silver ore from the district, and Mapes (12) has published a description of the Bote mine, including a brief geological history of the region. Although no report has been published on the Cantera mine, the author has had access to unpublished reports by García, Livingston and Vaupell.

Purpose and Methods of Present Investigation. The present paper was written during the winter of 1954–1955. The larger part of the field work was done during the first weeks of September, 1954, and the area was again visited for a few days in December of the same year. Petrographic studies and examinations of polished ore sections were done at Yale University during the winter of 1954–1955.

The area mapped consisted of a strip roughly a km long and 500 m wide along the Cantera Vein, within the area of the claims held by the Fresnillo Company. A topographic map of this area on a scale of 1:2,500 with a contour interval of 5 m was made with plane table and alidade, after plane table stations had been located by a transit and stadia survey. Underground geology was mapped at a scale of 1:500 on base maps supplied by the Fresnillo Company. Because of illness, the author was able to complete only the geology of the 90-meter level at the General Shaft. The 130-meter level at Santa Marta was visited and notes were made on the structure, but no geologic mapping was done.

Acknowledgments. The author is indebted to Mr. Hugh Rose, Managing Director of the Fresnillo Company, for permission to publish this paper. Dr. J. B. Stone of the Fresnillo Company suggested the problem and offered advice and equipment. The underground maps of the Cantera mine were supplied by the Engineering Department of the Fresnillo Company. Ing. Juan Rivas and Sr. Felipe Chaigres assisted in the field mapping. Drs. Bateman, Rodgers, Walton, and Jensen of Yale University offered advice, suggestions, and criticism.

GENERAL GEOLOGY

Lithology and Petrography

Shale.—The oldest rock in the area (Fig. 1) is the "Thonschiefer" or clay slate of Burkart, which occurs associated with altered gabbro in scattered localities to the north of the Cantera Vein. It is a light pinkish grey, medium-grained shale with a moderately well developed slaty cleavage. In the few places where it may be seen (principally on the north slope of the Cerro de la Cantera), the bedding is fairly regular, with layers from 10 to 30 cm thick. This bedding is not marked by striking differences in color or grain size, and is easily obscured by the mild metamorphism to which the rock has been subjected. Where unaltered, the rock weathers pale yellow, or locally light grey in color. Joints and cracks are commonly stained by iron oxides, and Burkart reports scattered pyrite (6, p. 28), which may not be primary, however.

In the vicinity of the Cantera Vein and near the cross-cutting quartz veins, the shale or slate has been silicified and altered to a light grey, aphanitic rock with poor slaty cleavage. In these areas, the rock tends to weather in shades of purple and dull green, especially along joint cracks.

Since no fossils have been found in this formation in the immediate area, there is considerable debate as to its age. Burckhardt and Scalia (5, p. 7) believe the formation to be Upper Triassic. Upper Triassic fossils have

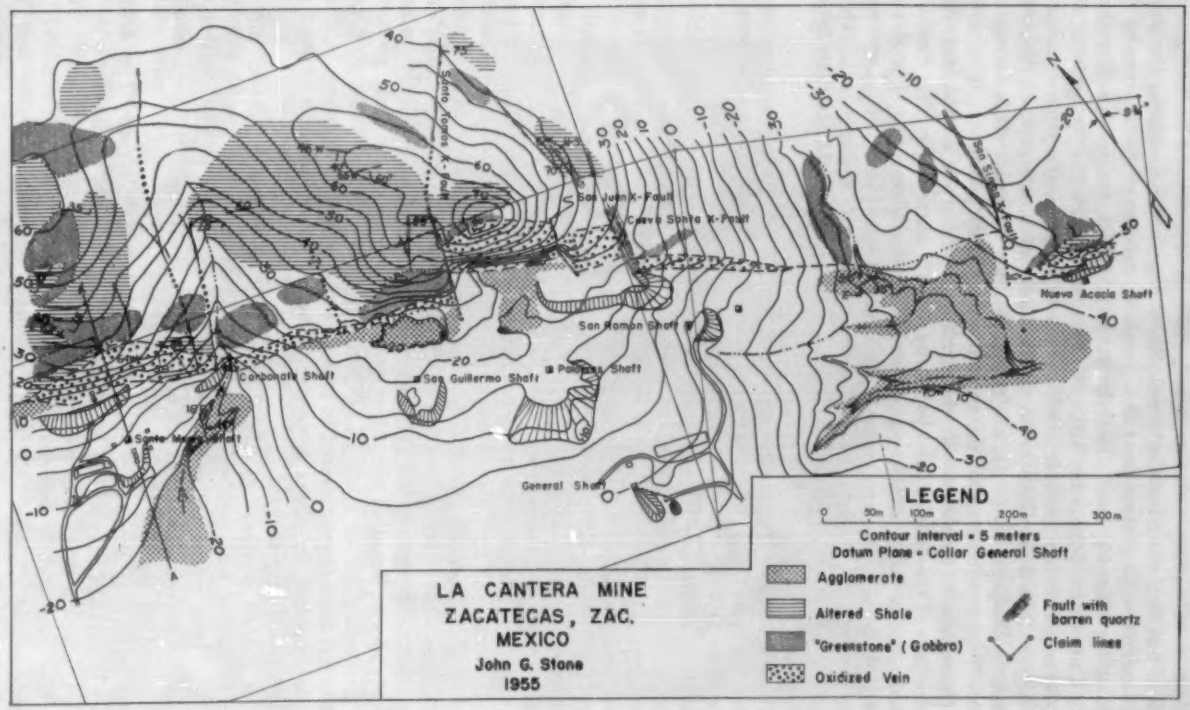

FIG. 1. Geologic map of La Cantera mine, Mexico.

been found in slightly metamorphosed slates in the Arroyo de la Calavera about 10 km to the west of the area. According to these authors, the slates are associated with greenstones, like the slates over much of the area to the north of the Cantera Fault. Botsford (4, p. 1227) assigns the formation to the Cretaceous, apparently with no basis other than that, in general, the Cretaceous period in Central Mexico was one of widespread marine deposition. The highly folded phyllites north of El Bote mine, assigned to the pre-Triassic by Mapes (12, p. 8), are probably older than this shale formation, and the Tertiary volcanics of the region are certainly younger.

"Greenstone" (Gabbro).—To the north and west of the Zacatecas Valley, a major part of the district is underlain by a much altered, greenish, medium-grained igneous rock, in places associated with the Mesozoic (?) shales or slates. Within the Cantera property, this rock is found in scattered outcrops to the north of the Cantera Vein. Underground, it is exposed in workings that penetrate into the footwall of the vein, as in the Santa Marta shaft below the 90-meter level.

The rock, generally known as "roca verde" or greenstone, has been classified differently by several authors, evidently owing to slight variations in composition from place to place.

At La Cantera, the rock is a dull greenish, crystalline, altered gabbro, composed principally of altered plagioclase feldspar and scattered crystals of pyroxene a millimeter or so in diameter. The rock is crossed by a network of minor fractures marked by rather extensive deuteric alteration.

In thin section, the rock is a much altered gabbro, originally with a hypidiomorphic-granular texture, apparently once composed predominantly of augite and acid labradorite (An_{55-60}) with a little accessory ilmenite. The pyroxene grains, once comprising about 25 percent of the rock, have been shattered and rather extensively altered to fibrous pale-green penninite and strongly pleochroic hornblende. Clusters of small crystals of epidote (probably an alteration product of the pyroxene) are scattered throughout the section. The plagioclase laths have undergone extensive sericitization. This labradorite is one of the major primary minerals of the rock, probably once accounting for as much as 60 percent of the volume. The accessory ilmenite has been largely altered to stringers and blebs of leucoxene. Calcite is fairly abundant, in places accompanied by very fine brownish crystals of an unidentified clay mineral.

The gabbro weathers to a dull olive-drab or yellowish brown, and is generally flecked with patches of black iron oxide and a few altered feldspar crystals. Joint cracks and weathered surfaces are stained by "limonite" to a dull reddish brown. Outcrops are not plentiful, occurring only where erosion has stripped off the thin coating of residual soil.

The gabbro is apparently intrusive into the shale series. The actual contact is exposed only in one locality on the north slope of the Cerro de la Cantera, where a thin sill of gabbro has been intruded into the shales. The shale has been slightly indurated close to the contact, but the alteration is not pronounced. Mapes (12, p. 12) believes that the andesites near El Bote farther to the west were intruded as a shallow stock. It is probable

that the andesite exposed at El Bote grades into the more basic rock around La Cantera, and that the mode of emplacement at the two places is similar. In other words, the gabbro at La Cantera was probably emplaced as a shallow stock, with a surrounding network of dikes and sills. The age of this intrusion is not definitely known, but it must have taken place at some time late in the Mesozoic or early in the Cenozoic, before the movement along the Cantera Fault that displaces the formation. Botsford (4, p. 1227) believes that the intrusion took place after the deposition of the Miocene (?) volcanic agglomerates in the region, but the fact that the agglomerate is composed largely of pebbles of gabbro casts doubt on this interpretation.

FIG. 2. Exposure of Zacatecas Agglomerate, 1 km south of La Cantera. Tuff overlain by agglomerate.

Zacatecas Agglomerate.—The youngest formation exposed at La Cantera is the agglomerate (Fig. 2) that crops out along the Zacatecas Valley from the city of Zacatecas to the village of Guadalupe 6 km to the east. The formation has been given the name "Guanajuato Conglomerate" by Botsford (4, p. 1227–1228), because of its resemblance to a similar conglomerate (also called the "Guanajuato Conglomerate") that is exposed at the famous silver camp of Guanajuato. The two formations are not continuous with one another, and are related only through possibly contemporaneous deposition during a period of widespread Cenozoic volcanism. The writer therefore proposes that the name "Guanajuato Conglomerate" be dropped as a designation for the formation in the Zacatecas district and the name "Zacatecas Agglomerate" be substituted.

The formation is composed of at least 200 m of coarse-grained, reddish rocks with basal sandstones and conglomerates grading up into poorly bedded volcanic agglomerates and tuffs (6, p. 42–46). The formation is overlain by thick rhyolites to the south of the Zacatecas Valley, and by the rhyolite capping of La Bufa north of the city of Zacatecas.

The agglomerate with interbedded tuff exposed at La Cantera evidently belongs in the upper part of the section as described by Burkart. It is composed of angular to sub-rounded pebbles of slate, greenstone and rhyolite a few centimeters across, with a few large blocks of dark, greenish black, fine-grained andesite as much as 70 cm in diameter (fig. 2), interbedded with irregular beds or lenses of pinkish white tuff. The matrix consists of small angular rock chips and bits of quartz cemented with a calcite cement.

A kilometer to the southwest of the General Shaft, a rather extensive mass of fine-grained pinkish rhyolite is interbedded with the agglomerate. This body of rhyolite was not studied in detail, but seems to represent a local flow that was extruded during the period of deposition of the agglomerate, and prior to the formation of the extensive flows that overlie the agglomerates.

Throughout the Cantera property, the agglomerate beds strike roughly north or northwest, and dip towards the west or southwest. At a distance of 50 or 60 m from the Cantera Fault, the beds are nearly flat lying, but on approaching the fault, they take on a steep southwest dip, due to drag along the fault.

Close to the mineralized portions of the fault, the agglomerate has undergone extensive alteration and silicification. The dull purple color has been bleached to a dull yellowish brown, and the outlines of the individual pebbles have been almost completely obscured. The result is a compact flinty rock crossed by minor veinlets of quartz exhibiting a microscopic comb structure. The alteration is best observed underground in a long crosscut such as the 90-meter level crosscut at the General Shaft (Fig. 4). On surface, the agglomerate seems to continue unaltered up to the hangingwall of the mineralized fault. This may be due to the slumping of unaltered material against the vein as the stopes above the 90-meter level were allowed to cave, or possibly to a combination of slumping and weathering.

The agglomerate is soft and easily weathered, and throughout much of the area is overlain either by residual soil or by wash derived from the vein outcrop and shale-gabbro complex.

Although to the writer's knowledge no fossils have been found associated with the agglomerates, they are probably middle or upper Miocene. During the latter part of the Miocene, much of Central Mexico was undergoing uplift, accompanied by extensive and widespread volcanism (8, p. 38), of which these agglomerates probably represent an early stage.

Geologic Structure

The general geologic structure of the Cantera property and nearby areas is that of a basin of agglomerates overlain by, and locally interbedded with rhyolites, downfaulted against a shale-gabbro complex (probably a stock with

associated sills and dikes) along a major normal fault striking generally N70°–80°W, and dipping at an average of 50° to the southwest. This fault, known as the Cantera Fault (or, where mineralized, as the Cantera Vein), is one of the major structural features of the Zacatecas district, forming the northern boundary of the agglomerates and rhyolites of the Zacatecas Valley for a distance of nearly 10 km. The Cantera Fault has been mineralized along much of its length, and in places, as at La Cantera, carries good lead-zinc-silver ores. Since the silicified portions of the fault resist weathering, it crops out as a series of prominent ridges from the Cerro del Pedernalillo 5 km to the east of La Cantera to La Bufa, 5 km to the west. At La Cantera,

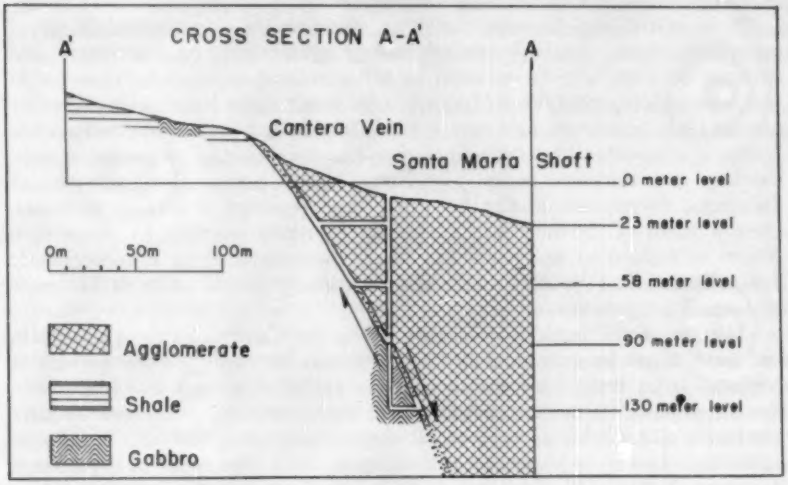

FIG. 3. Cross section of La Cantera Vein at Santa Marta.

the fault changes direction slightly, from about N60°W in the eastern part of the property to N72°W at Santa Marta. As seen in the cross-section through Santa Marta (Fig. 3) the dip of the mineralized fault (the Cantera Vein) increases slightly with depth.

The Cantera Fault has itself been cut, and in places offset, by a series of roughly parallel, steeply dipping faults striking north-northeast (Fig. 1). Four of these major cross-faults, the Santo Tomas, Cueva Santa, San Juan and San Simon are exposed in the area mapped, as well as several minor fractures. These cross-faults are marked by veins of white, glassy, nearly barren quartz containing silicified fragments of breccia or silicified gouge. Along most of the Cantera Fault, these cross-faults appear to occur in restricted zones, almost invariably associated with minable ores along the major fault (García, Unpublished report). For this reason, they have been considered as one of the factors localizing the rich zones of mineralization

along the Cantera Fault. For reasons more fully explained later, the author does not hold this view, but regards the cross-faulting as post-mineral, at least at La Cantera.

The initial movement along the Cantera Fault took place in the Miocene, at which time the region was undergoing uplift and the initial stages of the volcanism that was to culminate in the eruption of great amounts of Miocene rhyolites over much of Central Mexico. Although there is no direct evidence to support the hypothesis, it seems probable that the faulting was contemporaneous with the deposition of the agglomerate-rhyolite series, with the result that the basin gradually filled as it subsided. The subsiding basin evidently received some purely sedimentary material in addition to the pyroclastics, especially during the earlier stages of subsidence.

It is interesting to note that this structure—a downfaulted basin of pyroclastic rocks, perhaps underlain by sedimentary conglomerates and overlain by rhyolites—is common to other mining camps of Mexico. At Guanajuato, the famed Veta Madre lies for much of its length along a major normal fault similar to the Cantera Fault in that it brings a basin of middle Tertiary conglomerates, tuffs and rhyolites into contact with older sedimentary and intrusive rocks. At Fresnillo, 60 km to the northwest of Zacatecas, Stone and McCarthy (15) have reported a similar structure. Here a basin of Tertiary (?) sedimentary breccia overlain by more than 200 m of tuffaceous sediments has been downfaulted along a subsequently mineralized fault (the 2270 vein) against a gently folded series of Mesozoic shales and greywackes.

The age of the latest displacement along the Cantera Fault is unknown, but must have been later than the extrusion of the rhyolites (which it displaces at La Bufa), and earlier than the period of mineralization and vein formation, since the vein material has not been crushed or shattered by later movement along the fault. The total displacement along the fault is likewise unknown, since no volcanics have been preserved to the north of the present Zacatecas Valley. The thickness of agglomerate and rhyolite exposed at La Bufa indicates a displacement of at least 250 m. At La Cantera, 136 m of agglomerate may be observed in the General Shaft. At one time this shaft continued to the 192-meter level, but judging from the shaft dump, it did not encounter the underlying shales and gabbros.

Geologic History

Although the sequence of geologic events in the Cantera region is relatively clear, the lack of accurate age determinations makes it difficult to assign each event to its correct position in the geologic time-scale. The oldest rock exposed at La Cantera is the shale or "clay slate," probably deposited during the Mesozoic Era, possibly during the Late Triassic. At some time late in the Mesozoic or early in the Cenozoic, the shales were folded and intruded by a small basic stock with associated dikes, sills and andesitic volcanics.

Early in the Miocene, most of Central Mexico underwent uplift and

normal faulting on a large scale. This faulting resulted in scattered basins bordered by normal faults, of which the Zacatecas basin is an example. As the basin subsided, it was filled by debris, notably fragments of slate, andesite and coarse crystalline rocks worn from the upthrown block of the fault. Towards the end of the Miocene, there was an outbreak of volcanic activity over much of Mexico. In the Zacatecas district, the first stages of this volcanism resulted in thick deposits of coarse agglomerates or breccias interbedded with tuffs and local flows. This early explosive phase was followed by the eruption of a thick series of rhyolite flows that blanketed the area. These flows were cut by later movement along the Cantera Fault.

At some time after the Miocene, and before erosion had reached its present depth, hydrothermal solutions deposited quartz and metallic sulphides in restricted zones along the Cantera Fault. The mineralized Cantera Fault was then broken by a set of high-angle faults, which were subsequently filled with barren quartz.

Erosion at La Cantera since the last period of faulting and quartz vein formation has removed at least the 100 m (minimum) of rhyolite that once covered the area, and has removed on the order of 400 m of vein material that once extended above the present vein outcrop.

ORE DEPOSITS

History and Production.—According to García (Unpublished report), the ore deposit at La Cantera was first worked for silver by Pedro José Bernárdez early in the 1700's. The deposit must have been known before this, however, since actual mining had been going on in the district since 1548, and in the 150-year interval, such a prominent outcrop would doubtless have been visited by prospectors. The Bernárdez family worked the mine until 1786, when water and a shortage of supplies forced them to abandon it.

In 1871, Don José Nava organized a company to reopen and extend the workings. The Palomas Shaft was repaired, and work was carried down to a depth of about 150 m in the Palomas orebody (the portion of the vein between the Santo Tomas and Cueva Santa cross-faults). The old San Ramon and San Guillermo shafts were repaired, and drifts were driven on the vein at about the 65- and 120-meter levels. These workings apparently made little or no water, but were difficult to keep open, due to the soft ground on the hangingwall of the vein.

The company than sank the General Shaft to a total depth of 192 m, and cross-cut to the vein at the 173-meter level. However, workings along the hangingwall of the vein at this level made so much water that the company was unable to keep it down with horse whims, and was forced to abandon the mine.

La Cantera was worked by various individuals and small companies until 1936. Evidently some of these operators shipped small amounts of zinc ore to the smelter, but for the most part, they concentrated their efforts on whatever silver (zinc-free) ore their predecessors had left above the water table.

The Fresnillo Company took over the property in 1936, and mined a

considerable tonnage of relatively low-grade lead-zinc ore from the footwall of the vein. The Company suspended operations in 1940, but in 1948 leased the property to Jesús Dueñas. Dueñas sank the "Carbonate" shaft to a depth of about 10 m, and repaired and deepened the old Santa Marta Shaft. At present, he is mining from the 90- and 130-meter levels at Santa Marta, and from the 90-meter level at the General Shaft.

Primary Ore Deposit.—The primary ore deposit at La Cantera consists of a broad, irregular vein along the Cantera Fault, containing metallic sulphides and associated gangue. The primary ore minerals are pyrite, sphalerite, galena and chalcopyrite. The ores carry silver and some gold, but no silver minerals were recognized in the polished sections. Bastin (1) reports pyrargyrite and other silver sulphantimonides from other mines along the Cantera Vein, and it is probable that these minerals occur at La Cantera as well. The gangue minerals are chiefly quartz and calcite, and although

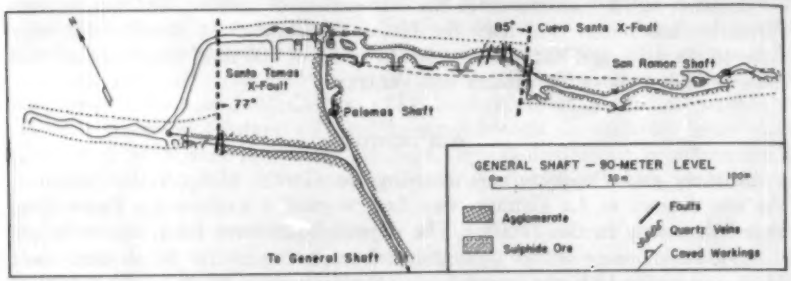

FIG. 4. La Cantera mine, 90-meter level, General Shaft.

Bastin (1) reports fluorite from the Cantera Vein, none was observed in the specimens collected.

The total width of the vein, including areas of intense wall-rock alteration, is as much as 30 m in places. The ore shoots are seldom more than 10 or 15 m wide, and generally include much waste, both as stringers and as small isolated fragments. In places (Fig. 4), the vein is apparently divisible into two parts—a silver-rich quartz vein on the hangingwall and a lead-zinc sulphide vein on the footwall. Livingston (Unpublished report, 1926) quotes several passages from an earlier report by Federico Sescosse, in which Sescosse discusses this feature of the orebody. He says: "The ores on the hangingwall, especially in the first or east ore shoot, are in simple combination, and therefore amenable to treatment (cyanidation); on the other hand, as the vein is entered, toward the middle, at the same time that the silver content decreases, the ores become rebellious and contain sulphides of lead and zinc." Unfortunately, early mining either completely removed the hangingwall portion of the vein or permitted the ground to cave. For this reason, the hangingwall vein is inaccessible on the 90-meter level at the General Shaft. The main vein evidently has a somewhat different structure

at Santa Marta, where a short cross-cut driven into the hangingwall showed low silver assays and no appreciable increase in quartz, as was evidently present in the silver ore referred to by Sescosse.

The sulphide vein on the footwall of the main lode is a breccia filling deposit in which there has been considerable replacement. The original breccia is a fault breccia composed predominantly of fragments of slate and gabbro, both of which have been highly altered (Fig. 5). The fragments of slate seem to have been especially susceptible to silicification, and appear as dull reddish-grey, flinty fragments embedded in the sulphides. The contact between the fragments and the sulphides is generally quite sharp, but in places the sulphides (especially the galena) have replaced the outer edges of the fragments. The gabbro fragments have been altered by hydrothermal solutions, but do not appear to have been as thoroughly silicified as the slate. They generally contain small scattered crystals of pyrite that have grown within them by replacement. The ore is slightly vuggy, with the vugs lined with quartz and calcite (Fig. 5).

Mineralogy and Paragenesis.—The chief primary minerals in a probable paragenetic sequence are:

1—quartz
2—sphalerite-chalcopyrite
3—galena
4—pyrite
5—quartz
6—pyrite
7—calcite

The position of the silver minerals in the sequence is uncertain. It is probable, however, that they are later than the galena, and earlier than the last of the quartz. One mineral reputed to be a silver sulphide was examined by X-ray methods and found to be alpha chalcocite (Servos and Farrand, personal communication). It occurs mixed with small blebs of pyrite which it appears to envelope; its exact position in the paragenetic sequence is uncertain, but it is probably supergene.

The sphalerite at La Cantera is a light yellow-brown resinous variety. At Santa Marta, the sphalerite surrounds the breccia fragments (Fig. 5), and is clearly younger than the galena. The deposition of the two minerals overlaps, and the galena does not seem to have replaced the sphalerite to any considerable extent. The sphalerite contains minute blebs and inclusions of chalcopyrite, probably the result of exsolution on cooling. Chalcopyrite also occurs scattered through the ore as discrete grains.

The early sulphides are cut by quartz veinlets showing crustification of quartz over pyrite and a micro comb structure in the quartz. The quartz crystals lining some of the small vugs have been coated by tiny pyrite crystals. At Santa Marta, these vugs were subsequently filled by calcite.

Oxide Zone.—The primary sulphides have undergone fairly complete, but spotty oxidation down to about the 30-meter level (J. B. Stone, personal

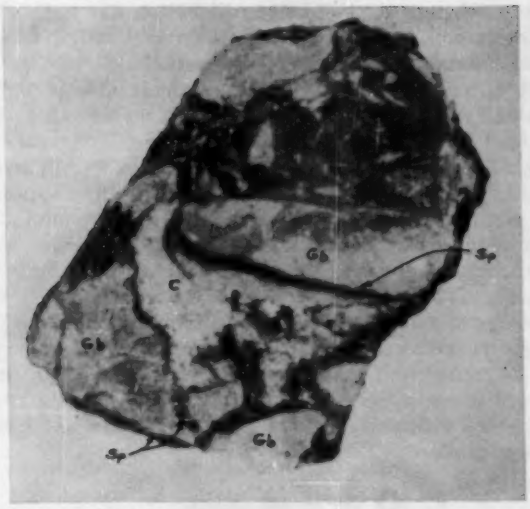

FIG. 5. Sulphide ore from 130-meter level Sta. Marta. Sulphides enclosing fragments of breccia (mostly gabbro); gb, gabbro; SP, sphalerite; C, calcite lining small vug.

communication), although ground water percolating down along minor fractures has resulted in narrow zones of alteration along these fractures at least as far down as the 90-meter level. The surface outcrop of the vein is completely devoid of sulphide relics, but the "Carbonate" shaft, sunk with the intent of exploring the possibilities for oxide ores, encountered remnants of pyrite, galena and other sulphides at a depth of about 10 m. The vein outcrop is marked by a prominent iron-stained gossan showing the "boxworks" characteristic of leached sulphide ores. The original sphalerite is represented both by coarse cellular and by light brown, fine cellular boxworks, and the original galena by yellowish "cleavage" boxworks. Some of the voids have been completely filled by soft, earthy, brick-red "limonite," and there are scattered bright red bands throughout the outcrop that have been saturated with transported "limonite" derived from the pyrite originally present in the vein. The bright red color of the transported "limonite" is thought by Blanchard to be characteristic of gossans over orebodies containing a relatively large proportion of pyrite to copper sulphides. At La Cantera, assays confirm this. Although copper is present (both as chalcopyrite and as chalcocite), and assays taken from the primary ores below the gossan at Santa Marta may show as much as 1.8 percent Cu, most parts of the vein contain only slight traces of copper.

Since the workings above the 90-meter level are caved, there is no way of proving whether or not there was any considerable enrichment of the primary sulphides. With the exception of the single specimen of chalcocite

given to the author by Dueñas, no supergene minerals were seen at the 90-meter level.

Structure and Origin of Deposit. As mentioned in the section of the paper dealing with the general geology of the area, the Cantera Fault has been broken by a series of high-angle faults trending approximately north-south (Figs. 1, 4). At La Cantera, 3 of these faults have broken the portion of the vein between the San Guillermo and San Ramon shafts into a series of 4 separate orebodies—the San Guillermo orebody bounded on the east by the Santo Tomas cross-fault; the Palomas no. 1 orebody between the Santo Tomas and San Juan faults; the Palomas no. 2 orebody between the San Juan and Cueva Santa faults; and the San Ramon orebody to the east of the Cueva Santa cross-fault. The other main cross-fault, the San Simon, lies to the west of the isolated San Simon orebody. Where these cross-faults cut the footwall complex of the Cantera Fault (gabbros and shales), they have been filled with white, glassy quartz. The quartz veins do not continue into the agglomerates, a fact that led Sescosse to believe that they were branches of the main Cantera Vein. From this, and from the fact that most of the mines along the Cantera Fault are located at places where the main fault is displaced by the system of north-south faults, he concluded that the presence of the cross-faults was the controlling factor in the mineralization along the major fault. This idea has apparently been accepted without question ever since. In 1906 Flores (7, p. 11) summed up this theory with the statement: "Notwithstanding its considerable length and width, the 'Cantera Vein' is in itself barren; it owes its richness to the north-south fractures that cut it perpendicularly, as one can observe that the mines of La Cantera and San Simon are located precisely at the intersection of these fractures." The observed features of the cross-faulting at La Cantera raise a number of serious objections to this hypothesis.

1) The cross-faults displace the orebodies. Underground, the quartz veins (generally accompanied by soft clay gouge) cut cleanly across the massive sulphides. The Santo Tomas cross-fault has brought the San Guillermo orebody into contact with unaltered agglomerates (near the hangingwall of the vein, the agglomerate is so highly altered that the outlines of the individual pebbles are almost completely obscured). Here, a quartz vein along the fault separates the agglomerates from the orebody.

2) The quartz veins, even where they cut across rich sulphide ores, are practically devoid of lead, silver, or zinc, and therefore could hardly have "enriched" the main Cantera Vein. In a series of samples taken along these cross-cutting quartz veins, the assay values in lead, silver and zinc (always low) tend to rise sharply close to the main orebody. This would seem to indicate that most of the metallic values in the quartz veins are due to contamination from the main orebody rather than to any metallic sulphides associated with the silica-bearing solutions that formed the veins.

The quartz veins contain silicified fragments of breccia, and it was thought by Vaupell (Unpublished report, 1936) that the barren quartz in the cross-veins represented a second period of mineralization and faulting, the first of which presumably enriched the main Cantera Fault. A sample

of the breccia fragments was taken and assayed. The assay value of these fragments is about the same as the value of the enclosing quartz, indicating that they do not represent an earlier period of mineralization by solutions containing appreciable amounts of metallic material.

This evidence suggests that the cross-cutting quartz veins are younger than the main orebody. The fact that they do not extend beyond the Cantera Fault into the agglomerates may be explained by the relative competency of the rocks on the two two sides of the fault. The gabbros and slates are relatively impervious, brittle rocks capable of sustaining a well defined fracture. The soft agglomerates, on the other hand, are relatively incoherent, and are highly permeable. Although they contain calcite veinlets a few centimeters wide along minor fractures, a large fault would be sealed by gouge or by slumping. Because of their high permeability, silica-bearing solutions would tend to diffuse into them, and would therefore not produce narrow, well defined veins.

Possibly the system of north-south fractures is due to the same forces that controlled the mineralization along the Cantera Fault. In other words, some force, possibly acting in a vertical direction, produced zones of weakness along the Cantera Fault, probably where the fault varied slightly in strike or dip. Solutions emanating from an unknown source would follow such zones of weakness, and would deposit localized orebodies. The escape of the mineralizing solutions possibly relieved the stresses on the area temporarily, but eventually the stresses in the mineralized areas (apparently still the most highly stressed zones along the fault) reached the point where they could no longer be tolerated, and fractures formed cutting across the orebodies. Silica-bearing solutions nearly devoid of metallic sulphides followed these cross-fractures, resulting in a system of north-south quartz veins closely associated with the various orebodies.

This hypothesis is necessarily somewhat vague, since this study does not cover more than the immediate area around La Cantera, and is therefore offered only as a tentative explanation to account for the apparently close relationship between the cross-faults and the orebodies at La Cantera. It may or may not be applicable elsewhere along the Cantera Fault.

Associated Eluvial Deposits.—On the south slope of the Cerro de la Cantera, there is an extensive cover of material eroded from the vein outcrop and from the resistant rocks on the footwall side of the Cantera Fault. Sescosse reported that several of the small haciendas in the vicinity were able to treat at a profit relatively large tonnages of ore picked from the deposit. Apparently some lots of this hand picked ore ran as much as 160 "marcos" of silver per ton (about 1,300 grams Ag/ton), but the usual tenor of the treated ore was much lower—about 3 or 4 "marcos" (250–260 grams) of silver per ton. The deposit, known as "boleo," consists of a blanket of crudely stratified wash as much as 5 m thick. The silver values are contained in the coarse fragments worn from the vein outcrop, probably from the quartz-silver hangingwall vein. These fragments are from 15 to 20 cm in diameter, and are found in irregular lenses scattered through the main blanket of wash.

Sescosse reported that the "boleo" covers the south side of the Cerro de la Cantera "down nearly to the Villa of Guadalupe" (Statement taken from Vaupell, 1936, unpublished report). It therefore blankets an area of roughly 8 hectares, with an average thickness of perhaps 2 m. Of this thickness, quartz worn from the outcrop of the hangingwall vein accounts for an estimated 10 cm (probably a conservative estimate). The amount of quartz material present, therefore, indicates that the amount of erosion that the vein has undergone since its formation is probably in the order of 400 m. This figure is merely an order of magnitude, but together with a consideration of the mineralogy, suggests that the veins were formed at a fairly shallow depth, possibly less than 1,000 m.

Conclusions. The orebody at La Cantera may be classified as an epithermal breccia-filling deposit in which there has been considerable replacement. The vein is known to have a vertical range of more than 250 m, and was probably formed at a fairly shallow depth. The orebody has been broken by later cross-faults with associated quartz veins, which at La Cantera exercise no control over the distribution of the ore shoots within the Cantera Vein.

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NEW HAVEN, CONN.
June 8, 1955

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DISCUSSION

A REVIEW OF THE FALCONBRIDGE ORE DEPOSIT

Sir: The literature covering the origin of the geology of the nickel-copper ores of the Sudbury District is voluminous and contains some masterpieces of geologic dissertation. The article by Lockhead in the January-February issue of ECONOMIC GEOLOGY is no mean addition to the knowledge of these important ore deposits. He is to be commended for the new factual material and for the constructive deductions that have been added.

However, his simple statement about the discovery of this ore, "The Falconbridge ore body . . . was first discovered by Thomas Edison about 1900 by geophysical methods," should be reviewed in the light of the actual facts.

To Edison must go the credit of inferring the possibility of the presence of nickel-copper ore in one section of a mile-long length of ore. To test his dip needle anomalies he staked a 40-acre claim, the SE¼ of the S½ of Lot 12, Concession IV, Falconbridge Township, Ontario. His test pit was abandoned in quicksand without discovering ore or even reaching ledge. According to reports current at that time he also tested by pits a number of other magnetic anomalies in this general area, and elsewhere in the Sudbury District, with negative results.

In my opinion, credit should be given for the discovery of the Falconbridge ore body to two men, William E. Smith and Hugh M. Roberts.

Smith was a lawyer who had studied enough geology in college to cause him to spend more time in prospecting than in practicing his profession. In 1915, while he was living in Sudbury and engaged in prospecting for iron ores to the northwest, he came to realize that explorable lands were still available for staking in the Sudbury District. He presented a staking program which was approved by Warren J. Mead, chief geologist of E. J. Longyear Company and Professor of Geology at the University of Wisconsin. Staking and drilling were to be undertaken in six or seven different townships, including Falconbridge Township which he regarded favorably even though heavily drift covered. His judgment proved to be well founded.

Roberts, geologist for E. J. Longyear Company (now a consulting geologist of Duluth), supported the general concept after a careful field check. The exploration project was financed by The Minneapolis and Michigan Development Company, comprising Minneapolis capital, under the direction of E. J. Longyear Company, with Roberts contributing a masterful plan of attack and the field implementation of this plan. The various places where drilling was to be undertaken were selected on the basis of A. P. Coleman's[1] map and report.

[1] Coleman, A. P., 1913, The nickel industry with special reference to the Sudbury Region, Ontario: Can. Dept. Mines, Mines Branch, Pub. 170.

Roberts proved early in the exploration that testing magnetic anomalies alone might not lead to the discovery of ore, because at the commencement of the project in January, 1916, Roberts made some preliminary observations with a dip needle in the Falconbridge area at the place where Edison sank his uncompleted test pit and confirmed a definite magnetic attraction. However, there were other magnetic attractions over norite outcrops to the north as well as magnetic attractions over outcrops of greenstone to the south. Roberts' conclusions were that a much broader approach to the probable existence of ore in this area should be made on the basis of covering a very wide area instead of exploring on the limited location of one out of several magnetic anomalies. Roberts' methods of approach as well as his theories as to existence of ore were substantiated abundantly by discovery of one of the world's greatest ore bodies.

In Falconbridge Township claims were staked in a zone of sufficient width to assure the ownership of the contact between norite and foot-wall rocks. Roberts took charge of the work. Diamond drills were moved in and program of scout drilling inaugurated under which one hole was put down on each 40-acre claim with the object of (1) making a valid discovery, (2) doing the assessment work, and (3) "bracketing" the norite-foot wall contact so as to limit as much as possible the area in which ore exploration should be conducted. After bracketing the contact with scout holes, Roberts' plan was to pinpoint its location more exactly with vertical holes and then to intersect the norite-greenstone contact with angle holes. The end results of this process was, in the spring of 1916, the discovery of ore in the SE¼ of the S½ of Lot 10, Concession IV, about a mile east of the so-called Edison forty. A few weeks after the ore was discovered, I had the privilege of arriving on the job as a junior geologist just out of school. After the initial discovery of ore and a master plan of attack as laid out by Roberts, it was a fairly simple matter by using ordinary geologic interpretations and geometric calculations to trace, by drilling, the ore body westerly through the Edison forty where ore was eventually found by diamond drills in July, 1916.

A more detailed description of the features of this ore body and its discovery and exploration, as known at the completion of this preliminary exploration, is covered by Roberts and Longyear.[2]

Without any intention of detracting from Edison's brilliance, it is my opinion, from firsthand knowledge, that credit for the discovery of this ore should go to Hugh M. Roberts and William E. Smith and not to Edison as given in this article.

ROBERT D. LONGYEAR

E. J. LONGYEAR COMPANY,
MINNEAPOLIS 2, MINNESOTA,
August 30, 1955

[2] Hugh M. Roberts and Robert D. Longyear, 1918, Genesis of the Sudbury nickel-copper deposits as indicated by recent exploration: Trans., Am. Inst. Min. Eng., v. 59, p. 27–56; also published jointly in Trans., Can. Min. Inst., v. 21, p. 80–117.

GEOLOGY AND IRON ORES OF STEEP ROCK LAKE

Sir: The paper by A. W. Joliffe (ECON. GEOL., vol. 50, p. 373–398, 1955) is a highly interesting new contribution to the literature of an unusual iron ore occurrence with regard to paragenesis and origin. Two visits to the deposits have convinced the writer that Dr. Joliffe's conclusions need modification. Only two points may be discussed here. The well-known "Steep Rock Limestone" described by a number of investigators is a much localized formation with a maximum thickness of perhaps 500 ft. It is unusually pure in places where later hydrothermal processes have not converted it into ferruginous dolomitic rock. In places this formation contains unsorted fragments of pyroclastic material parallel to what appear to be original bedding planes of the highly folded limestone and replacing dolomites. How did they get into the limestone? One familiar with regions of late volcanic activity and thermal spring deposits, for example, with the Hopi Buttes, Arizona, and Yellowstone Park, has seen large travertine beds that contain pyroclastics in layers or in random patterns. The fragments evidently were contributed by nearby volcanic activity. The algal structures observed in this limestone strengthen the belief that we are dealing with an ancient metamorphosed travertine. The fact that it has been found only on or in the vicinity of Steep Rock Lake is also in favor of such a restricted origin. Following the travertine, chemical deposition of iron minerals and "ashrock" debris could have completed the Steep Rock sequence of sediments, provided one does not subscribe to the hypothesis of hydrothermal replacement of limestone and ashrock by the iron ores as advanced by Roberts and Bartley and accepted by many investigators.

Dr. Joliffe's interpretation that the goethite (limonite) of the present ore is early meets with very serious objections. The Steep Rock Group went through at least one severe stage of metamorphism (Algoman) at the time it was intruded by or was at least very close to a batholith. It would have been practically impossible for goethite ore to have persisted through this cycle. There is plenty of evidence that pyrite as lenses and concretions is a common constituent in parts of the ore, particularly near the hanging wall and "feathering ends" of bodies. Siderite may have been another common mineral. Both of these could have formed at a later stage of hot springs activity soon after the travertine, or as a replacement along the ashrock-limestone contact. They would have been quite durable through the metamorphic stage as is shown by the pyritic "ores" of the Atikokan and Michipicoten ranges in this region. It may be suggested that the "pisolitic" textures that occur in small amounts could also have been concentric concretionary pyrite-siderite forms, at least in part. Goethite then would be a later post-metamorphism oxidation product along the "ore zone." It would have been produced by vigorous groundwater circulation particularly along the numerous brecciated zones. Whether this happened in the dying stages of volcanism following Algoman intrusions, or perhaps in Keweenawan time, is not any better known than what caused deep circulation of the water. At any rate, this almost complete change from pyrite and siderite to goethite with resulting shrinkage would

have required oxidizing conditions and temperatures not exceeding 150°. There is plenty of chemical evidence accumulating which shows that sulfur can be almost entirely removed in such reactions.

The observation that some fine-grained hematite seems to be later than dense goethite has caused much of the confusion with regard to the hypothetical paragenesis and origin. The hematite could have been earlier or contemporaneous with pyrite and siderite. Any oxidation of these two minerals to goethite where surrounded by hematite would certainly give the impression that the hematite was later. Some polished sections the writer has studied are of this type, but there are others in which hematite may very well be slightly later. There is, of course, no good reason why pyrite or siderite must always alter to goethite. On the Mesabi range for example, siderite alters to goethite and hematite.

JOHN W. GRUNER

UNIVERSITY OF MINNESOTA,
MINNEAPOLIS 14, MINNESOTA,
August 29, 1955

PRECAMBRIAN BANDED IRON ORES

Sir: In his "Contribution to studies of origin of Precambrian banded iron ores," published in vol. 50, no. 5 of ECONOMIC GEOLOGY, p. 466, Mr. Eugene A. Alexandrov states that "only Spencer and Percival deny the presence of organisms in the basins of deposition."

We made no such denial. In the paper to which Mr. Alexandrov refers (ECON. GEOL., vol. 47, p. 380) we wrote:

> Although we do not consider these granules to represent algae or bacteria, nor to be other than inorganic spherulites, this is, of course, no argument against the existence of such organisms, and they may well have played an important part in the formation of these rocks.

E. SPENCER AND F. G. PERCIVAL

HASLEMERE, SURREY,
ENGLAND,
August 29, 1955

REVIEWS

Atomic Energy Research at Harwell. By K. E. B. Jay. Pp. 144; pls. 19; figs. 9. Philosophical Library, New York, 1955. Price, $4.75.

The author, who is Principal Scientific Officer at Harwell since 1947, continues from his report of 1952, which dealt with progress from 1946–1951, and brings it up to August 1954, when the U. K. Atomic Energy Authority took over. Also, changes in international agreements permit release of former secret information. There are two parts: Part I deals with major programs, written mainly for non-technical readers; Part II treats in detail of selected researches and is intended primarily for scientific readers. Part I is preceded by a glossary which gives the meaning of technical terms for the lay reader.

Part I treats of advances in the production, reactor, isotope programs, electronic instruments, extra-mural research, special techniques and engineering and human programs. Part II takes up research in the divisions of physics, chemistry and chemical engineering, and metallurgy.

It is a concise little book, valuable for reference by the layman or the atomic scientist.

Outside Readings in Geography. By Fred E. Dohrs, Lawrence M. Sommers, and Donald R. Petterson. Pp. 805; figs. 35. Thomas Y. Crowell Company, New York, 1955. Price, $2.95.

This bulky volume is made up of 80 separate writings from as many authors. These writings, by authors from several countries, have been grouped into twelve chapters, each representing a major area of interest. The chapter headings are: The Scope and Tools of Geography, Weather and Climate, Landforms, Natural Vegetation of Forestry, Soils and Agriculture, World Water Resources, Mineral Production, Manufacturing, Trade and Transportation, Population and Settlement, Political Geography and Geopolitics, The Regional Concept. Each chapter is made up around eight to ten writings under the name of each author and carries a page or two of introductory matter by the editors. Each individual reading is preceded by a headnote, a footnote giving the reference, and a brief biographical sketch of the author.

The purpose of the volume is to assemble outstanding readings in geography, to make available collateral readings to complement textbooks, and to enrich courses of instruction in geography by providing supplementary material. The editors appear to have made a broad and careful selection of writings that relate to each of the chapter headings.

Electrons, Atoms, Metals and Alloys. By William Hume-Rothery. Pp. 387; figs. 171. Philosophical Library, New York, 1955. Price, $10.00.

This book is intended for the reader to whom a mathematical text-book is unattractive. Its four parts cover the nature of an atom, a metal, an alloy, and the structure of the nucleus. It was first published in 1948 and revised this year to bring it up to date. It covers rather broadly modern thought respecting the four

substances. It is written for the metallurgist but is meant also to serve as an introduction to modern atomic theory. The entire book is written in the form of a dialogue between an older metallurgist and a young scientist, which method of treatment extends the subject and after a bit becomes tiresome reading.

Soil and Water Conservation Engineering. By RICHARD K. FREVERT, GLENN O. SCHWAB, TALCOTT W. EDMINSTER and KENNETH K. BARNES. Pp. 479; illus. John Wiley and Sons, New York, 1955. Price, $8.00.

The authors cover in this single volume both soil and water conservation engineering. They present a concise review of hydrology and soil physics and offer an integrated treatment of conservation from an engineering standpoint. They supply the field data to illustrate practical applications. The chapters cover such subjects as precipitation, infiltration, evaporation, runoff, soil erosion and various types of controls, headwater flood control, both surface and subsurface drainage and drains, pumping, irrigation, land clearing and legal aspects of conservation.

It is an excellent reference work for both hydrologists and soil engineers.

Industrial and Manufacturing Chemistry. Part I, Organics by GEOFFREY MARTIN; seventh edition by EDWARD I. COOKE, assisted by E. S. SELLERS, J. L. FERGUS, P. C. BISHOP, R. A. JONES, D. E. PARTINGTON, D. W. IZOD, I. McARTHUR. Pp. 752. **Part II, Inorganic;** 2 vols., sixth edition by WILFRED FRANCIS, assisted by N. BERKOWITZ, M. FRANCIS, A. B. SEARLE, vol. 1, 600 pp.; vol. 2, 491 pp. Philosophical Library Inc., New York, 1955. Price, $50.00.

This is an old established treatise that has been brought up to date to supply a demand for the rapidly growing field. Part I, organic, in 24 sections, treats all of the chief organic industries. Part II, inorganic, deals with fuels, gases, water, acids, salts and chemicals in volume 1. Volume 2 takes up disinfectants, fertilizers, and materials relating to the mineral kingdom. The two parts are a collosal work of compilation and description and covers most of the chemical manufacturing field.

BOOKS RECEIVED

KURT SERVOS

Bibliography and Index of Geology Exclusive of North America. MARIE SIEGRIST, M. C. GRIER and others. Pp. 689. Geological Society of America, Vol. 19, New York, 1955.

Metallurgical Progress—2. Pp. 71. Philosophical Library, New York, 1955. Price, $6.00. *Contains three critical reviews: Preparation of Ores by J. M. McLeod; Electrical Steel Production by D. D. Howat, and Non-Metallic Inclusions by H. B. Bell. Each section deals with the newer data on these subjects.*

Mineral Resources, Navajo-Hopi Indian Reservations, Arizona-Utah, Volume III, Construction Materials. G. A. KIERSCH. Pp. 81; figs. 27; tbls. 7. Bureau of Indian Affairs, University of Arizona, Tucson, 1955. *Construction materials consist of natural aggregate, crushed stone, dimension stone, lightweight aggregate, and rip-rap.*

Annual Report for 1954. Pp. 39. Bechuanaland Geological Survey, Lobatsi, 1954. Price, *Sh.* 3/-.

The Geology of British Guiana and the Development of its Mineral Resources. G. M. STOCKLEY. Pp. 102; pls. 7. British Guiana Geological Survey, Georgetown, Demerara, 1955. Price, BG $3.00. *Annual diamond production is about 35,000 carats; gold, 20,000 oz. Useful deposits include bauxite (65 million tons ore in reserve), Mn (4 to 5 m. t. ore reserves), and columbite.*

Minerales, No. 50. Pp. 43. Instituto de Ingenieros de Minas de Chile, Santiago, 1955.

Geologic Map of the Gold Coast. 1 sheet. Gold Coast Geological Survey, Accra, 1955. Scale, 1:1,000,000.

Bolétin, Tom. IV, No. 9. Pp. 1591–1776. Centro de Documentacion Cientifica y Tecnica, Mexico, 1955.

Los Problemas Juridicos y Economicos de la Mineria del Azufre en relacion con los de la Industria Minero-Metalurgica Mexicana. A. T. BENITEZ. Pp. 79. Camara de Senadores, Primera Comision de Minas, Mexico, 1955.

Supplement, 1955 to the Statistical Yearbook, 1954: Tin, Tinplate and Canning. Pp. 91. International Tin Study Group, The Hague, 1955. Price, $1.75.

Geological Map of Japan. Hirado. Pp. 36. Geological Survey of Japan, Hisamoto-Cho, 1955. *Several coal seams, some of them strongly coking, are being worked. Text in Japanese, résumé in English. Geologic map, 1:50,000.*

Ohio Fossils. Aurele La Rocque and M. F. Marple. Pp. 152; figs. 413. Ohio Geological Survey, Bull. 54, Columbus, 1955. *This informative and comprehensive booklet for the layman should be very useful to the undergraduate student.*

Bolétin de la Escuela Nacional de Ingenieros, Ser. IV, Tom. XXVIII. Pp. 80 Escuela Nacional de Ingenieros, Lima, Peru, 1955.

Annales de la Société Géologique de Pologne, Vol. XXIV, Fasc. 1. Pp. 116, tbls. 10. Société Géologique de Pologne, Krakow, 1955. Price, Cena zl. 21,–. *One paper deals with stratigraphy, another presents a tentative genetic classification of breccias (sedimentary, tectonic, diagenetic, magmatic and metamorphic breccias).*

Communicacões dos Serviços Geologicos de Portugal, Tom. XXV. Pp. 312. Serviços Geologicos de Portugal, Lisboa, 1955. *Of eleven diverse papers six deal with paleontology.*

The Determination of Southern Rhodesian Economic Minerals. N. E. BARLOW. Pp. 33. Southern Rhodesia Geological Survey Bull. No. 42. *This abbreviated guide is useful in the field and laboratory. Total value of mineral production through 1950 is £257 million. Mineral map, 1:2,000,000.*

The Soils of Mbozi (Mbeya District). A. M. SPURR. Pp. 35; pls. 4. Geological Survey Dept., Dar Es Salaam, Tanganyika, 1955. Price, *Sh.* 7/50. *Soil map, 1:100,000; geological reconnaissance map, 1:125,000.*

Miocene Equidae of the Texas Gulf Coastal Plain. J. H. QUINN. Pp. 102; pls. 14; figs. 5; tbls. 25. Bureau of Economic Geology, Austin, Texas, 1955. Price, $1.75. *Three new genera and nine new species lead to a revised phylogeny of the horse.*

Characteristics of Minable Coals of West Virginia. J. W. HEADLEE and others. Pp. 166; figs. 68; tbls. 57. West Virginia Geological Survey, Vol. XIII (A), Morgantown, 1955.

Annual Report of the Geological Survey Department. Pp. 38; tbls. 3. Geological Survey, Entebbe, Uganda, 1954. Price, *Shs.* 1/75. *Wolfram is by far the most valuable of many economic mineral commodities.*

Results of an Investigation into the Possible Presence of Oil in Karroo Rocks in Parts of the Union of South Africa. S. H. HAUGHTON, J. J. BLIGNAUT, P. J. ROSSOUW, J. J. SPIES and S. ZAGT. Pp. 130; figs. 11; maps 8. Geological Survey of South Africa, Mem. 45, Pretoria, 1953. Price, 10 *s. Drilling for oil in the Karroo System was economically unsuccessful but provides many new geological data.*

California Division of Mines—San Francisco, 1955.

Bull. 165. Geology and Mineral Deposits of Barstow Quadrangle, San Bernardino County, California. O. E. BOWEN, JR. Pp. 208; pls. 9; figs. 84. Price, $5.00. *Economic minerals include barite, copper, dolomite, ganister, gold, iron, lead, limestone, magnesite, pyrophyllite, silver, wolfram, zinc, and ornamental marble and granite. Thirty-two differential thermal analysis curves of clay are appended. Geologic map, 1:125,000.*

Special Rept. 44. Bibliography of Marine Geology and Oceanography, California Coast. R. D. TERRY. Pp. 131, figs. 2. Price, 75 cts.

University of California Publications in Geological Sciences—Berkeley, 1955.

Vol. 30, No. 4. Granulites and Mylonites of the Region about Cucamonga and San Antonio Canyons, San Gabriel Mountains, California. K. JINGHWA HSU. Pp. 223–252; pls. 30–42; figs. 9. Price, $2.50.

Vol. 31, No. 2. A Survey of Various Late Cenozoic Vertebrate Faunas of the Panhandle of Texas, Pt. I. Introduction, Description of Localities, Preliminary Faunal Lists. C. J. JOHNSON and D. E. SAVAGE. Pp. 27–50; figs. 6. Price, 35 cts.

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Canada Department of Mines—Ottawa, 1955.

List 5–2. Petroleum Refineries in Canada. Pp. 16. Price, 25 cts. *At the end of 1954 Canada had 41 operating refineries with a capacity of more than 500 million bbl daily.*

Tech. Paper 10. Electronic Concentration of Low Grade Ores with the Lapointe Picker. A. H. BETTENS and C. M. LAPOINTE. Pp. 7; figs. 6. Price, 25 cts.

No. 844. The Canadian Mineral Industry, 1952. Pp. 198. Price, $1.00. *Canadian mineral production in 1952 was more than $1.2 billion. Metals, industrial minerals, and fuels are reviewed individually.*

Société Géologique de France—Paris, 1954.

Bull. Tome 4, Fasc. 7–9. Pp. 453–811; pls. 21–32; figs. 50. *Various papers deal with the geology of France and her colonies.*

Compte Rendu Sommaire des Séances. Pp. 61–208; 436–505. *The Proceedings include all papers communicated orally.*

Illinois Geological Survey—Urbana, 1955.

Circ. 199. Aromatic Fluorine Compounds as Fungicides. G. C. FINGER, F. H. REED, and L. R. TEHON. Pp. 15; tbls. 2.

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Circ. 199. Aromatic Fluorine Compounds as Fungicides. G. C. FINGER, F. H. REED, and L. R. TEHON. Pp. 15; tbls. 2.

Circ. 200. Preliminary Report on Uranium in Hardin County, Illinois. J. C. BRADBURY, M. E. OSTROM, and L. C. MCVICKER. Pp. 21; tbls. 5; fig. 1. *All samples analyzed for U_3O_8 contained less than the minimum of 0.1% required by the AEC.*

Circ. 201. Unpublished Reports on Open File, I. Mineral Fuels. M. B. BROPHY. Pp. 9.

Circ. 202. Sizing Studies on Plot-Oven Coke, Comparison with Commercial Coke Size. H. W. JACKMAN and R. L. EISSLER. Pp. 7; tbls. 4.

Circ. 203. Uranium in Illinois Black Shales. M. E. OSTROM and others. Pp. 15; fig. 1; tbls. 3. *None of the 175 samples meets the AEC minimum grade requirement for ore.*

Circ. 204. The Geneva (Middle Devonian) Dolomite in Illinois. H. R. SCHWALB. Pp. 7; figs. 4.

Illinois Petroleum 74. Oil and Gas Industry in Illinois, January 1, 1955. A. H. BELL, V. KLINE and W. F. MEENTS. Pp. 12. *Geologic map, 1:633,600.*

Geological Survey of India—Calcutta, 1950–53.

Records, Vol. 81, Pt. 3. The Mineral Production of the Indian Union during 1947. W. D. WEST. Pp. 389–563; tbls. 57. Price, *Rs.* 3/12. *In 1947 the value of the minerals produced in the Indian Union was £47.8 million.*

Records, Vol. 83, Pt. 1. Pp. 396. Price, *Rs.* 8/6. *General report of the Survey for 1949. Geological map, 1:6,082,560.*

Mem., Vol. 82. The Geology and Gem-Stones of the Mogok Stone Tract, Burma. L. A. N. IYER. Pp. 100; pls. 8. Price, *Rs.* 4/12. *The gem stones are ruby, sapphire, and spinel but there are also semi-precious stones and other economic mineral commodities.*

Indiana Geological Survey—Bloomington, 1955.

Bull. 8. The Geology of Miami County, Indiana. W. D. THORNBURY and H. L. DEANE. Pp. 44; pls. 8; fig. 1. Price, $1.00. *The most important economic products are sand and gravel, and oil and gas. Geologic map, 1:125,000.*

Field Conf. Guidebook 8. Sedimentation and Stratigraphy of the Devonian Rocks of Southeastern Indiana. H. H. MURRAY. Pp. 73; pls. 7. Price, $1.00. *The crushed stone, sand and gravel produced during 1953 had a value of more than $20 million.*

State Geological Survey of Kansas—Lawrence, 1955.

Bull. 110. Geology and Ground-Water Resources of Graham County Kansas. G. C. PRESCOTT, JR. Pp. 98; pls. 10; figs. 7; tbls. 7. *The rocks range in age from late Cretaceous to recent. Geologic map, 1:101,376.*

Bull. 112. Oil and Gas Developments in Kansas during 1954. W. A. VER WIEBE and others. Pp. 215; pls. 2; figs. 16; tbls. 57. *During the year 122 new oil pools and 22 new gas pools were discovered. Production totaled 118 million bbl oil and 405.8 billian cu. ft. natural gas.*

Vol. 13. Geology, Mineral Resources, and Ground-Water Resources of Osage County, Kansas. Pt. I, Rock Formations of Osage County. HOWARD G. O'CONNOR; **Pt. 2, Mineral Resources of Osage County.** E. D. GOEBEL and others; **Pt. 3, Ground-Water Resources of Osage County.** H. G. O'CONNOR. Pp. 50; pls. 4; figs. 3; tbls. 6. *Mineral resources include coal, clay, limestone, sand and gravel. Geologic map, 1:63,360.*

Ontario Department of Mines—Toronto, 1955.

Annual Rept. Vol. LXIII, Pt. 1, 1954. Pp. 104. *The total value of Ontario minerals reached a record in 1953 of $475 million.*

Annual Rept., Vol. LXIII, Pt. 2, 1954. Pp. 155. *Information and statistics for mining operations in 1953.*

Pennsylvania Topographic and Geologic Survey—Harrisburg, 1955.

Special Bull. 7. Atlas of the Butler Quadrangle, Pa. W. S. LYTLE and LILLIAN HEEREN. 9 maps.

Bull. W11. Ground Water Resources of Bucks County, Pa. D. W. GREENMAN. Pp. 66; pls. 2; fig. 1; tbls. 6. *Geologic map, 1:62,500.*

Quebec Department of Mines—Quebec, 1955.

Geol. Rept. 66. St. Jean-Beloeil Area. T. H. CLARK. Pp. 83; figs. 3. *Currently producing mineral deposits are all nonmetallic. Two geologic maps, 1:63,360.*

The Mining Industry of the Province of Quebec in 1953. Pp. 111; pls. 8; figs. 2. *Quebec's mineral production during 1953 had a value of more than $250 million.*

Senckenbergische Naturforschende Gesellschaft—Frankfurt am Main—1955.

Senckenbergiana Lethaea, Band 36, Num. 1/2. Pp. 190; pls. 19; figs. 59; tbls. 2. *Eight diverse papers on paleontology.*

Abh. 491. Stratigraphie und Mikrofauna des mittleren Malm im nordwestdeutschen Bergland. GERNOT SCHMIDT. Pp. 76; pls. 18; figs. 2. *The descriptions of Jurassic foraminifera include several new species.*

Tasmania Department of Geology—Hobart, 1955.

Publ. 28. The Orocline Concept in Geotectonics, Pt. I. S. W. CAREY. Pp. 225–288. *A theory of impressed strain satisfactorily explains orogenic belts. This bold concept rigorously probes orthodox geologic thought and may have wide repercussion.*

Publ. 30. Clay Minerals from Permian Strata of Tasmania. G. E. HALE and J. G. BRILL. Pp. 231–235; fig. 1. *Montmorillonite, nontronite and glauconite are useful stratigraphic marker minerals.*

U. S. Geological Survey—Washington, D. C., 1955.

Prof. Paper 268. The Central Kuskokwim Region, Alaska. W. M. CADY, R. E. WALLACE, J. M. HOARE, and E. J. WEBBER. Pp. 132; pls. 9; figs. 38. Price, $3.75. *Mercury is the chief mineral product (5,000 flasks during 1940–1950); commercial gold deposits occur as placer concentrations; wolfram has various associations. Cupriferous sulphides with associated gold, silver, and tin have not been developed commercially. Geologic map, 1:316,800.*

Prof. Paper 262. Pleistocene Geology of Eastern South Dakota. R. F. FLINT. Pp. 173; pls. 7; figs. 36. Price, $3.00.

Prof. Paper 274-B. Dakota Group in Northern Front Range Foothills, Colorado. K. M. WAAGÉ. Pp. 15–49; figs. 15. Price, 45 cts.

Bull. 1009-G. Uranium Deposits in Fall River County, South Dakota. HENRY BELL and W. E. BALES. Pp. 211–233; pls. 5; figs. 6. *Individual deposits vary greatly in grade.*

Bull. 1009-H. Geology of the Happy Jack Mine, White Canyon Area, San Juan County, Utah. A. F. TRITES, JR. and R. T. CHEW, III. Pp. 235–248; pls. 2; figs. 2. Price, 40 cts. *Uranium is produced from high-grade deposits in the Shinarump conglomerate.*

Bull. 1015-D. Chromite Deposits in Central Part Stillwater Complex, Sweet Grass County, Montana. A. L. HOWLAND. Pp. 99–121; pls. 4; fig. 1; tbls. 3. Price, $1.50. *Geological factors are unfavorable for obtaining any large tonnage of chromite; development would be both expensive and difficult. Four geologic maps.*

Bull. 1015-I. Geology of the Dry Valley Quadrangle, Idaho. E. R. CRESSMAN and R. A. GULBRANDSEN. Pp. 257–270; pl. 1; figs. 2. Price, $1.00. *The Phosphoria formation contains two minable zones of phosphate rock.*

Bull. 1017. Lead-Zinc Deposits of Cordillera Blanca and Northern Cordillera Huayhuash, Peru. A. J. BODENLOS and G. E. ERICKSEN. Pp. 166; pls. 12; figs. 33. Price, $2.75. *The most common minerals are galena (argentiferous), sphalerite and pyrite. Most deposits are fissure filling veins with some replacement bodies.*

Hawaiian Volcanoes During 1952. G. A. MACDONALD. Pp. 15–108; pls. 14; figs. 28; tbls. 11. Price, 55 cts. *Between June 27 and November 10, 1952, Kilauea volcano produced 64 million yds³ of new lava.*

Bull. 1021-C. Geologic and Airborne Radioactivity Studies in the Rock Corral Area, San Bernardino County, California. R. M. MOXHAM, G. W. WALKER and L. H. BAUMGARDNER. Pp. 109–125; pls. 2; figs. 4.

Bull. 1024-B. Investigations for Radioactive Deposits in Southeastern Alaska. W. S. WEST and P. D. BENSON. Pp. 25–57; pls. 3; fig. 1; tbls. 7. Price, 55 cts. *No uranium deposits of commercial value were found.*

Bull. 1025. Bibliography of North American Geology, 1951. R. R. KING, V. M. JUSSEN, J. S. POMEROY and V. L. SKITSKY. Pp. 378. Price, $1.75.

Bull. 1027-G. Lithium Resources of North America. J. J. NORTON and D. McK. SCHLEGEL. Pp. 325–250; fig. 1; tbls. 5. Price, 15 cts. *The tin-spodumene belt of the Carolinas is now the largest source of lithium in the world.*

Bull. 1033-B. Geophysical Abstracts 161, April–June, 1955. M. C. RABBITT, D. B. VITALIANO, S. T. VESSELOWSKY and others. Pp. 75–137. Price, 25 cts.

Bull. 1036-B. Rapid Determination of Germanium in Coal, Soil and Rock. HY ALMOND, H. E. CROWE and C. E. THOMPSON. Pp. 9–17; pl. 1; figs. 2. Price, 15 cts. *About 50 coal samples can be analyzed per man-day.*

Water-Supply Paper 1240. Surface Water Supply of the United States, 1952. Pt. 6-B, Missouri River Basin below Sioux City, Iowa. Pp. 455; figs. 3. Price, $1.50.

Water-Supply Paper 1241. Surface Water Supply of the United States, 1952. Pt. 7, Lower Mississippi River Basin. Pp. 523; figs. 3. Price, $1.75.

Water-Supply Paper 1267. Water Levels and Artesian Pressures in Observation Wells in the United States, 1953. Pt. 3, North-Central States. Pp. 254; figs. 27. Price, $1.00.

Water-Supply Paper 1268. Water Levels and Artesian Pressures in Observation Wells in the United States, 1953. Pt. 4, South-Central States. Pp. 218; figs. 38. Price, 75 cts.

Water-Supply Paper 1273. Surface Water Supply of the United States, 1953. Pt. 2-A, South Atlantic Slope Basins, James River to Savannah River. Pp. 284; figs. 3. Price, $1.00.

Water-Supply Paper 1275. Surface Water Supply of the United States, 1953. Pt. 3-A, Ohio River Basin Except Cumberland and Tennessee River Basins. Pp. 587; figs. 3. Price, $2.00.

Water-Supply Paper 1277. Surface Water Supply of the United States. Pt. 4, St. Lawrence River Basin. Pp. 361; figs. 3. Price, $1.25.

Water-Supply Paper 1283. Surface Water Supply of the United States. Pt. 9, Colorado River Basin. Pp. 472; figs. 3. Price, $1.50.

Water-Supply Paper 1286. Surface Water Supply of the United States, 1953. Pt. 12, Pacific Slope Basins in Washington and Upper Columbia River Basin. Pp. 407; figs. 3. Price, $1.50.

Water-Supply Paper 1295. Chemical Quality of Surface Waters in Devils Lake Basin, North Dakota. H. A. SWENSON and B. R. COLBY. Pp. 82; pls. 4; figs. 24; tbls. 19. Price, 75 cts.

Water-Supply Paper 1316. Compilation of Records of Surface Waters of the United States through September 1950. Pt. 12, Pacific Slope Basins in Washington and Upper Columbia River Basin. Pp. 592; pl. 1; figs. 2.

Water-Supply Paper 1327. Ground-Water Resources of the Prairie Creek Unit of the Lower Platte River Basin, Nebraska. R. T. SNIEGOCKI. Pp. 133; pls. 8; figs. 12; tbls. 9.

Water-Supply Paper 1329-A. Water-Power Resources in Upper Carson River Basin, California-Nevada. H. L. PUMPHREY. Pp. 29; pls. 2; figs. 2; tbls. 4. Price, 50 cts.

Water-Supply Paper 1330-A. Water Requirements of the Pulp and Paper Industry. O. D. MUSSEY. Pp. 71; pl. 1; figs. 21; tbls. 20. Price, 20 cts. *This report is one of a series describing water requirements of selected industries that are of national importance.*

SOCIETY OF ECONOMIC GEOLOGISTS

ANNUAL MEETING, 1956, NEW YORK CITY

The Annual Meeting for 1956 will be held February 20–23 at the Statler and New Yorker Hotels, in cooperation with the Annual Meeting of the American Institute of Mining and Metallurgical Engineers through the Geology Subdivision of the Mining-Geology-Geophysics Division and the Industrial Minerals Division of the Institute.

The Annual Dinner will be in the Penn Top Room at the Statler Hotel at 7:00 P.M., Tuesday, February 21. Dress is informal; tickets will be procurable at the registration desk. The dinner will be preceded by cocktails and followed by a brief business meeting.

All scientific sessions of the Society of Economic Geologists will be held in the Statler Hotel in rooms to be announced at the Registration Desk.

SCIENTIFIC SESSIONS

MONDAY, FEBRUARY 20, 2:30 P.M.

ORE DEPOSITS—GENERAL SESSION

GILBERT H. CADY and FRANK EBBUTT, *Co-Chairmen*

A. E. Moss and J. Schwellnus: The Quebec-Labrador ore and its relationship to the Sokoman formation.
W. H. Gross: Flow direction of ore solutions as an exploration guide at the Blyklippen mine, East Greenland.
A. D. Mutch: A critical evaluation of the classification of ore deposits of magmatic affiliations.
Michael Fleischer: Minor elements in sulfides.
Robert G. Coleman: The occurrence of selenium in sulfides from sedimentary rocks of the western United States.
Gunnar Kullerud: The FeS-ZnS geological thermometer.

TUESDAY, FEBRUARY 21, 9:00 A.M.

DEPOSITS OF RARE METAL SOURCES

PAUL F. KERR and LOUIS MOYD, *Co-Chairmen*

Jerry C. Olson: Association of rare-earth metals with alkalic rocks at Mountain Pass, California and other localities.
Robert B. Rowe: The Oka alkaline complex and associated columbium deposits.
A. F. Banfield: Geology of columbium and tantalum deposits.
E. P. Kaiser: Recent discoveries of niobium minerals in alkalic rocks of the United States.
E. Wm. Heinrich: Economic geology of the yttrium-group elements.

TUESDAY, FEBRUARY 21, 2:00 P.M.

LATE STAGES OF CRYSTALLIZATION AND RELATED ORE DEPOSITS

ALBERT E. WEISSENBORN and F. S. TURNEAURE, *Co-Chairmen*

George J. Neuerburg: Deuteric alteration and its possible significance to wallrock alteration in some rocks of the Boulder Batholith, Montana.

M. R. Klepper and Forbes Robertson: Part I.—Late magmatic phenomena in the northern part of the Boulder Batholith, Montana.

Forbes Robertson, D. M. Pinckney, and M. R. Klepper: Part II.—Notes on sequence of vein formation in the northern part of the Boulder Batholith, Montana.

W. T. Pecora: Late Eocene metallogenetic epoch in the Bearpaw Mountains, Montana.

Reno H. Sales and Charles Meyer: Genetic significances of quartz-molybdenite mineralization in the Butte District, Montana.

Willard C. Lacy: Igneous activity and related ore deposition in Peru, South America.

WEDNESDAY, FEBRUARY 22, 9:00 A.M.

THE NATURE OF ORE SOLUTIONS

J. T. SINGEWALD, JR. and GLENN C. WATERMAN, *Co-Chairmen*

Edwin Roedder and Lloyd L. Ames, Jr.: Composition of fluid inclusions.

R. W. Boyle: The geochemistry and origin of carbon dioxide, water, sulphur, and boron in the Yellowknife gold deposits, Northwest Territories, Canada.

Robert M. Garrels: A geologic interpretation of some aspects of the chemistry of ore fluids.

George W. Morey: The solubility of solids in gases.

J. L. Kulp and W. H. Ault: Sulfur isotopes and the origin of ore-forming fluids.

B. S. Butler: Mineralizing solutions that carry and deposit iron and sulphur.

WEDNESDAY, FEBRUARY 22, 2:00 P.M.

GEOLOGY OF NON-METALLIC MINERAL DEPOSITS

JOSEPH L. GILLSON and JOHN G. BROUGHTON, *Co-Chairmen*

W. N. McAnulty: Fluorspar deposits in Coahuila, Mexico.

Ralph J. Holmes: Opal deposits near San Juan del Rio, Queretaro, Mexico.

Conrad Martin and H. P. Willard: Quality control in the selective mining of magnesite at Gabbs, Nevada.

James B. Cathcart: Economic geology of the phosphate deposits of Florida.

G. Donald Emigh: Comments on the occurrence and origin of phosphate in Tennessee and in the Phosphoria Formation of the West.

John B. Patton: Economic geology of Salem limestone in the Indiana building stone district.

THURSDAY, FEBRUARY 23, 9:00 A.M.

GENERAL ORE DEPOSITS

FRANCIS CAMERON and JULIAN W. FEISS, *Co-Chairmen*

Frank G. Snyder and John A. Emery: Geology in development and mining, Southeast Missouri lead belt.

R. M. Knutson: Structural sections and the third dimension.
G. M. Wright: Geological mapping by light helicopter, N.W.T., Canada.
F. Stearns Cook and E. T. Wiley: The geology of the Woodrow Mine, New Mexico.
John W. Gabelman: Structural control of uranium deposits in the Zuni-Mt. Taylor Region, N.W. New Mexico.
S. W. Holmes: Geology and mineralogy of the Pronto uranium deposit district of Algoma, Ontario.

ABSTRACTS

GEOLOGY OF COLUMBIUM AND TANTALUM DEPOSITS

A. F. BANFIELD

Behre Dolbear and Company, Inc., New York, New York

Columbium and tantalum almost invariably occur together, generally as a mineral of the columbite-tantalite series, or pyrochlore-microlite series (including koppite). Production comes only from columbite-tantalite ores.

Columbite and tantalite occur in important amounts as: (1) primary constituents of albite-biotite-granite (Nigeria) and pegmatites (Belgian Congo, Uganda, United States, South West Africa); (2) in placers, associated with cassiterite (Nigeria, Malaya), with gold (French Equatorial Africa), or alone (British Guiana); (3) in bauxite and bauxitic clay (United States).

Pyrochlore-microlite minerals are associated with rocks high in carbonate, commonly together with alkalic intrusives, and with apatite, rare earth and uranium minerals. Pyrochlore occurs: (1) as an accessory in carbonatite (Tanganyika); (2) in albite-riebeckite-granite (Nigeria); (3) in carbonate and alkalic rocks (Oka and North Bay, Canada). Koppite is found in limestone (Western Germany) and in carbonatite-alkalic rock complexes (Norway). Titanium minerals sometimes contain columbium (Magnet Cove, Arkansas).

World production of columbite-tantalite in 1954 was 3594 long tons as follows: (1) *Columbite*—Nigeria (2689—two-thirds from placers, one-third from washing weathered albite-biotite-granite), Malaya (111—placers); (2) *tantalite (with columbite)*—Belgian Congo (532—placers, weathered and unweathered pegmatites), Brazil (170); (3) *remainder* in mixed concentrates from Portugal, Uganda, South West Africa, French Guiana, Southern Rhodesia, Australia, British Guiana, United States.

Substantial tonnages of pyrochlore are indicated at Oka and North Bay (Canada), Panda Hill (Tanganyika), Sukulu (Uganda), Mrima Hill (Kenya), and of koppite at Sove (Norway). In 1955 metallurgical tests and economic studies were reported under way at these properties.

THE GEOCHEMISTRY AND ORIGIN OF CARBON DIOXIDE, WATER, SULPHUR, AND BORON IN THE YELLOWKNIFE GOLD DEPOSITS, NORTHWEST TERRITORIES, CANADA[1]

R. W. BOYLE

Geological Survey of Canada, National Museum, Ottawa, Canada

The gold deposits of Yellowknife occur in two distinct geological settings. The principal economic deposits occur in quartz-carbonate lenses in extensive chlorite schist zones (shear zones) cutting greenstone (amphibolite) rocks. The other

[1] Abstract published by permission of the Acting Deputy Minister, Dept. of Mines and Technical Surveys, Ottawa, Canada.

deposits, of less economic importance, occur in quartz lenses in meta-sedimentary rocks.

Geochemically, the deposits in the greenstones represent concentrations of silica, carbon dioxide, water, sulphur, arsenic, antimony, gold, and other metallic elements. Those in the sediments represent concentrations of silica, sulphur, boron, gold and other metallic elements.

For the deposits in the greenstones chemical evidence is presented to show that, under the influence of a strong thermal gradient promoted by granite emplacement, the carbon dioxide and water in the original volcanic rocks were mobilized and migrated into the extensive shear zone systems. In the shear zones the chemical equilibrium was severely displaced, water and carbon dioxide reacted with the amphibolite rock producing extensive widths of chlorite and chlorite-carbonate schist, and silica, sulphur, gold and other elements present in the rock were mobilized. These mobilized elements and compounds migrated into dilatant zones such as shear zone junctions and were precipitated as quartz, sulphides, and metallic elements.

A similar process has operated to form the gold-quartz lenses in the meta-sediments. In these rocks silica, boron, sulphur, and metallic elements have been mobilized during the metamorphism of the sediments, and these have migrated into and been precipitated in dilatant zones in faults, fractures, and drag folds in the rocks.

MINERALIZING SOLUTIONS THAT CARRY AND DEPOSIT IRON AND SULPHUR

B. S. BUTLER

Department of Geology, University of Arizona, Tucson, Arizona

For years the writer has collected and published data on the primary (hypogene) occurrence of sulphates in metal deposits.

This paper attempts to apply those data to explain, in part, the transportation of metals that form primary (hypogene) ore deposits in sulphate solution and their deposition in the metal deposits in other chemical combinations, mainly oxides, sulphides, etc.

ECONOMIC GEOLOGY OF THE PHOSPHATE DEPOSITS OF FLORIDA

JAMES B. CATHCART

U. S. Geological Survey, Denver Federal Center, Denver, Colorado

Phosphate deposits of Florida are divided into river-pebble, hard-rock, and land-pebble types.

River-pebble deposits, bars, and floodplains of present streams are small, coarse-grained, and low in P_2O_5 content.

The hard-rock deposits occur in the lower part of the Alachua formation (Pliocene). The formation is probably the collapsed and partially stream-reworked residuum of the Hawthorn formation (early and middle Miocene). Deposits are small, but the very coarse phosphate particles are high in P_2O_5.

The land-pebble deposits, a part of the Bone Valley formation (Pliocene), were deposited on the Hawthorn formation by a transgressing sea which partly reworked and sorted the residual mantle of the Hawthorn. The phosphate deposits are large, unconsolidated, and flat-lying, and may be classified as: (1) reworked deposits of bedded coarse-grained phosphate; (2) residual deposits of massive fine-grained phosphate; and (3) deposits in which reworked material overlies residual material.

The P_2O_5 content of the phosphate particles varies inversely with grain size; thus coarse phosphate deposits are of lower grade than fine deposits.

Intensive weathering has altered the upper part of the Bone Valley formation to a zone characterized by very fine-grained aluminum phosphate minerals. This leached zone is a large potential reserve of phosphate.

The differences in size, phosphate content, and physical characteristics are a result of the geologic conditions which formed the deposits and are reflected in the prospecting, mining, and processing of the deposits.

THE OCCURRENCE OF SELENIUM IN SULFIDES FROM SEDIMENTARY ROCKS OF THE WESTERN UNITED STATES

ROBERT G. COLEMAN

U. S. Geological Survey, Washington 25, D. C.

Investigation of the minor and trace element content of sulfides associated with uranium ore from sandstone-type deposits has shown that selenium commonly substitutes for sulfur. The Morrison and Entrada formations of Jurassic age and the Wind River formation of Eocene age seem to be seleniferous stratigraphic zones; sulfides deposited within these formations consistently contain abnormal amounts of selenium. The selenium content of these sulfides is much greater than that reported in previously published data. The sulfides from the same stratigraphic zone usually contain the same relative amounts of selenium regardless of their position with respect to the uranium ore deposits. The maximum selenium content found in the various sulfide minerals is:

Mineral	Selenium (percent)
Pyrite and marcasite (maximum from published data)	0.0250
Marcasite	0.65
Pyrite	5.00
Chalcocite	5.00
Galena-clausthalite	18.00

Sulfides from the Chinle and Shinarump formations of Triassic age usually contain less than 3 ppm selenium except for those in the Temple Mountain mining district, Utah. Sulfides from the Temple Mountain deposits contain as much as 0.5 percent selenium. The selenides clausthalite and eucairite have been identified from several uranium ore deposits in the Morrison formation. Oxidation of these sulfides underground or in damp cool places produces a characteristic pink bloom of monoclinic native selenium which may invert to the more stable hexagonal native selenium at higher temperatures on the surface. Many of these sulfide concentrations represent a primary deposit of selenium, and, in view of the present critical shortage of this element, these sulfide concentrations associated with uranium ore deposits could furnish an economic source of selenium.

THE GEOLOGY OF THE WOODROW MINE, NEW MEXICO

F. STEARNS COOK AND E. T. WYLIE

The Anaconda Company, P. O. Box 638, Grants, N. M.

Anaconda's Woodrow Mine, on the Laguna Indiana Reservation in Valencia County, New Mexico, has produced uranium ore from a nearly vertical, pipe-like structure in the Jurassic Morrison Formation.

The inside of the pipe, from 20 to 30 feet in diameter, has been dropped from 25 to 40 feet in relation to the surrounding rocks. Uranium oxides, pyrite and minor amounts of other minerals occur in or near the resulting gouge and brecciation. Mining has been in process to the 100 foot level. Drilling has revealed that mineralization occurs at greater depth. The origin of the deposit, though still in doubt, is believed by the writers to be hydrothermal.

COMMENTS ON THE OCCURRENCE AND ORIGIN OF PHOSPHATE IN TENNESSEE AND IN THE PHOSPHORIA FORMATION OF THE WEST

G. DONALD EMIGH

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This paper is in the form of progress comments on the author's studies of phosphate deposits in Tennessee and the West—chiefly in Idaho. Comments are based on field and petrographic work and related chiefly to the occurrence, origin, and weathering effects of phosphate.

The blue rock and brown rock Tennessee deposits are made up of fossils—wholly or partly phosphatized. These are mostly crinoids, bryozoa, and brachiopods. No oolitic structure has been observed. The brown rock deposits are residual, resulting from removal by weathering of carbonates from the underlying low-grade phosphatic limestones. The blue rock deposits are the original deposition of phosphate in limestone.

The origin of the phosphate in the Permian Phosphoria formation of Utah, Idaho, Wyoming, and Montana is not as clear cut as the Tennessee phosphate, although a portion at least is similar to that in Tennessee, i.e., phosphatized fossils. In southeastern Idaho phosphate is not confined to the lower Phosphoria shale section, but considerable amounts are present throughout the upper 200-foot Rex Chert member. Lesser amounts are also found in the Pennsylvanian Wells limestone underlying the Phosphoria—at least to depths of about a hundred feet.

A brief description of the Rex Chert and suggestions as to origin are presented, as are suggestions as to the origin of the oolitic structure occurring in some of the phosphate nodules in the Phosphoria.

The importance of weathering of the Phosphoria is mentioned, with attendant changes not only in grade of ore, but in the phosphate nodules themselves.

MINOR ELEMENTS IN SULFIDES

MICHAEL FLEISCHER

U. S. Geological Survey, Washington 25, D. C.

A review of more than 300 published papers has shown that few generalizations can be made that lead to successful prediction of which ore minerals are most likely to contain which minor elements. Predictions based on ionic radii are not satisfactory. The most hopeful approach is that based on tendency of an element to form certain types of bonds; for example, germanium and indium tend to form tetrahedral bonds in sulfides and are therefore most likely to occur in minerals with structures resembling that of sphalerite (for instance, chalcopyrite, stannite, enargite).

Estimates of temperature of formation based on minor-element content must be treated with great caution, but the data indicate that gallium and germanium are

generally highest and indium is lowest in low-temperature deposits. The ratio Se″ : S in pyrite may be a useful guide to temperature of formation. Exceptions to such generalizations are to be expected.

Few determinations have been made of the distribution of minor elements between two co-existing minerals, yet such data are essential not only from the theoretical, but also from the practical viewpoint, as illustrated by the distribution of cobalt and nickel among pyrite, pyrrhotite, and chalcopyrite. Quantitative analyses of carefully purified minerals of known geological history are badly needed.

STRUCTURAL CONTROL OF URANIUM DEPOSITS IN THE ZUNI–MT. TAYLOR REGION, N.W. NEW MEXICO

JOHN W. GABELMAN

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Early Tertiary compression produced the west-northwest Zuni uplift, with large northeast cross folds and cross fault zones. Small diagonal, cross, and longitudinal folds are common in limestone and local in sandstone. On the southeast the Zuni uplift abuts against the nearly contemporaneous northeast McCarty syncline which contains the Miocene Mt. Taylor volcano. This zone of abutment contains a band of Pleistocene basalt cones, a fluorspar district in the Zuni core and the Grants uranium district.

Belts of uranium mineralization extend incompletely around both major structures with strongest mineralization in the fringe of the intersection zone. The intersection zone and each structure center are suggested as solution sources. Within belts ore districts occur at intersections of certain large cross folds with cross zones, or simply in cross or outlying folds. Each district contains a unique combination of host rocks and structural controls.

The Grants district contains five isolated smaller districts, each localized along the coincidence of cross synclines and cross fault zones. Orebodies are localized in minor "shear" anticlines in Todilto limestone and in Morrison sandstone lenses.

The Ambrosia Lake district is along the coincidence of a major diagonal anticline and a diagonal fault zone. Orebodies occupy sandstone lenses near the anticlinal crest.

The Gallup Hogback district involves cross folds and faults. Orebodies occur in minor anticlines and in sandstone and in shale lenses.

The Laguna district appears controlled by subtle folds. Orebodies occur in anticlinal crests, structural terraces, and pipes.

Mineralization in the Miguel Creek faulted dome area occurs in faults.

A GEOLOGIC INTERPRETATION OF SOME ASPECTS OF THE CHEMISTRY OR ORE FLUIDS

ROBERT M. GARRELS

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Attempts to define the physical and chemical characteristics of the ore-transporting medium have consistently failed, and the range of possible compositions is still great. However, some progress has been made in defining its general nature, chiefly from geologic rather than theoretical chemical considerations. If attention

is confined to low-temperature deposits, such as the Mississippi Valley type lead-zinc ores, it becomes apparent that the ore fluid is not like ordinary ground waters below the water table. From its effects on host rocks, the ore fluid has a viscosity and density of the same order of magnitude as water at room temperature; the solubility of the ore metals in the fluid is approximately the same or greater than that of calcite; the differential solubility of the ore metals is very slight, compared to that in pure water; wall rock alteration is comparable to that expected from nearly neutral and reducing aqueous solutions. Furthermore, it is probable that changes in the fluid caused by solution of calcite are responsible for deposition of the metals in replacement deposits. A fluid with such properties conceivably could result from the alteration of the properties of pure water by large concentrations of dissolved neutral chlorides, hydrogen sulfide and carbon dioxide. The possibility of two fluid phases cannot be disregarded.

FLOW DIRECTION OF ORE SOLUTIONS AS AN EXPLORATION GUIDE AT THE BLYKLIPPEN MINE, EAST GREENLAND

W. H. GROSS

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Lead-zinc ore occurs in a steep dipping fault zone at the Blyklippen Mine. The direction of flow of ore-bearing solutions, which are assumed to have brought in the lead-zinc mineralization, has been indicated by an analysis of growth zones in crystals, lead-zinc ratios, the structure environment, and the decrepitation of ore samples. Knowledge of the flow direction has proven to be a useful guide in the exploration for new ore at the mine.

ECONOMIC GEOLOGY OF THE YTTRIUM-GROUP ELEMENTS

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Two relatively recent developments have greatly stimulated search for commercial deposits of yttrium minerals: 1) the Spedding-Voigt method of separation of the individual members of the group and 2) discovery that certain elements of the group have considerable potential value in the atomic energy program. Securing moderate to large amounts of yttrium elements involves three problems: 1) raw material supply, 2) separation and extreme purification of the individual elements as oxides and 3) preparation of the metals.

Minerals relatively rich in yttrium elements are chemically of two types: 1) those also rich in Cb and Ta, which require alkali fusion for their decomposition; examples—samarskite, euxenite, fergusonite, yttrotantalite; 2) those without appreciable Cb or Ta, which are acid leachable without fusion; examples—xenotime, gadolinite.

Such minerals are found only in pegmatites, granitic rocks (xenotime) or in placers derived from them. Possible non-pegmatitic sources for large scale production from minerals with relatively low yttrium contents (1–5%) include 1) brannerite deposits, 2) thorite deposits and 3) zircon deposits. In the exploitation of these deposits yttrium elements would be by-products to the separation of U, Th and Zr, respectively. Minor to moderate amounts of yttrium elements also occur in fluorites, potash feldspars, garnets, scheelite, apatite and sphene, but these occurrences are at present commercially not significant.

OPAL DEPOSITS NEAR SAN JUAN DEL RIO, QUERETARO, MEXICO

RALPH J. HOLMES

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The results of one phase of a broader program dealing with the origin and mode of transport of natural silica are presented. A review of the literature indicates that no detailed investigation of any of the opal deposits of Mexico has hitherto been published. The few papers that exist were either based on work carried out in the last century or are superficial locality descriptions. No petrographic study of any of the deposits appears to have been made.

Opal of gem quality has been reported from numerous localities in no less than seven Mexican states. The most renowned, though not the oldest, is the district northwest of San Juan del Rio, a town about 30 miles each of Queretaro, where opal deposits occur in siliceous lavas.

This discussion is based largely on field studies made in the San Juan del Rio area and subsequent laboratory investigation of the material collected there. Petrographic data on the lava with special attention to rock alteration in the vicinity of the opal bodies are presented. The paragenetic relations of the opal to the associated minerals, and the question of origin of the deposits are discussed. X-ray, optical and other physical data on the opal are presented.

GEOLOGY AND MINERALOGY OF THE PRONTO URANIUM DEPOSIT DISTRICT OF ALGOMA, ONTARIO, CANADA

S. W. HOLMES

Pronto Uranium Mines, Algoma Mills, Ontario, Canada

The main rock formation occurring on the property of Pronto Uranium Mines Limited comprises two structural units, quite distinct in age and easily distinguished from one another. These units are from oldest to youngest: (1) a pre-Huronian granitic basement upon which the younger rocks lie; (2) a thick succession of Huronian quartzite formations lying unconformably upon the pre-Huronian basement. Uranium mineralization is found in three rock types. These are in order of abundance: (a) a quartz pebble conglomerate occurring at the base of the Huronian sediments; (b) the lower quartzite member of the Huronian sediments where the conglomerate is not present; (c) the "old" soil regolith or transition zone occurring between the basement rocks and the overlying sediments, where the conglomerate is missing. This is composed of grits, greywackes and related rock types. The uraniferrous pebble conglomerate which constitutes the bulk of the ore shows considerable variation in thickness and disposition because of irregularity and unevenness of the pre-Huronian surface on which it was deposited. It is a fairly continuous horizon, however, and conforms to the east-west trend and gentle southerly dip of the overlying sediments. The uranium values are chiefly contained in the titanate brannerite and its alteration products. Small amounts of uraninite and sooty pitchblende are also present. Pyrite is the most abundant accessory mineral, being present in amounts up to 15 percent. Minor amounts of chalcopyrite, pyrrhotite, galena, monazite, rutile, anatase, magnetite, and zircon have been observed. All of these minerals occur as disseminated blebs and aggregates within the material cementing the pebble conglomerate. The genesis of the uranium mineralization will continue for some time to be a point of conjecture. It may be said, however, that the results of studies made at Pronto favor a placer origin with possible later hydrothermal modification.

RECENT DISCOVERIES OF NIOBIUM MINERALS IN ALKALIC ROCKS OF THE UNITED STATES

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At Potash Sulphur Springs, Ark., recent studies have shown that soil overlying the nepheline syenite-carbonatite complex locally contains as much as 0.24 percent niobium in yellow pyrochlore. The bedrock host is not known. By contrast, at the similar Magnet Cove complex several miles to the east, niobium occurs in the titanium minerals rutile, perovskite, and sphene; no niobate minerals such as pyrochlore have been found.

Alkalic intrusive rocks of New England and eastern Canada lie in a zone 1,000 miles long and a few hundred miles wide that trends northwesterly across other major geologic features. Recent discoveries in eastern Canada of pyrochlore deposits in carbonatites related to alkalic rocks prompted reconnaissance of the New England area during the past summer. No carbonatites were found but at Litchfield, Maine, boulders of radioactive soda syenite were found to contain as much as 0.3 percent niobium in radioactive minerals, probably of the pyrochlore type.

Elsewhere in the United States pyrochlore occurs in minute quantities in the Conway granite of New Hampshire, in nepheline syenite pegmatite near Wausau, Wis., in syenitic pegmatite near Pikes Peak, Colo., and in numerous quartz-bearing pegmatites.

LATE MAGMATIC PHENOMENA IN THE NORTHERN PART OF THE BOULDER BATHOLITH, MONTANA

M. R. KLEPPER [1] AND FORBES ROBERTSON [2]

Late magmatic phenomena herein described include a stage in which feldspar is stable and one in which it is destroyed. As the batholith crystallized, a differentiate rich in silica and potash evolved. This residue crystallized: (1) within the crystal mesh of the quartz monzonite as "aplitic" groundmass or as potash feldspar porphyroblasts, generally with associated interstitial quartz; and (2) as discrete bodies of alaskite, aplite with or without pegmatite, and quartz porphyry, some of which are segregations in situ, with or without marginal replacement, but most of which are fracture fillings by material which in some instances may have migrated thousands of feet. Commonly tourmaline and pyrite, and less commonly molybdenite, crystallized in essentially a feldspar-stable (deuteric) environment during the late stage of consolidation of the alaskitic and aplitic rocks.

In at least one body of quartz prophyry, pyrite, marcasite, sphalerite, galena, and chalcopyrite crystallized under conditions of partial feldspar destruction, probably in an essentially closed system in an environment intermediate between deuteric and hydrothermal. In addition the presence of abundant tourmaline with feldspar in many aplitic rocks and of tourmaline with feldspar alteration products in many veins suggests a close genetic relationship of late-stage igneous and hydrothermal processes.

Timing and localization of fracturing largely determined what portion of the late fractions of the magma crystallized in more or less "disseminated" form in situ; what portion migrated along fractures and crystallized as discrete dikes of felsic rock; and what portion yielded sulfide-bearing veins and their alteration envelopes.

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STRUCTURAL SECTIONS AND THE THIRD DIMENSION

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Conventional structural sections inadequately portray geometrical relations. A plane is represented by its trace line, an ambiguous procedure which on structural maps is clarified by adding the dip symbol and figure. The acute angle between a structural plane and a vertical plane of section is now termed the *angle of departure*. It is measured in a plane normal to the trace line. This angle relates the structure to the vertical section just as the dip relates it to the (horizontal) map. The departure is expressed as a function of the strike intersection and apparent dip. Reference of the two latter angles to an alignment diagram therefore gives the angle of departure. Commonly a simple graphic-trigonometric solution suffices.

Conventional sections omit lineations altogether: fold axes, mineral alignments, preferred orientations, etc. Their introduction to structural sections is also feasible, and should often be clarifying. The normal projection of the lineation must first be plotted on the section. The term *apparent plunge* is proposed for the inclination which such a normal projection will assume on the vertical section. The minimum angle between the lineation and the plane of section, now termed the *angle of penetration*, compares to the angle of plunge of the geologic map. The apparent plunge and angle of penetration are derived, expressed as functions of known angles, and presented as alignment diagrams.

This system permits structural sections to express available data in three dimensions as effectively as structural maps. Similarity of such augmented sections to structural maps facilitates their study.

THE FeS–ZnS GEOLOGICAL THERMOMETER

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The concentration of elements in mix-crystals under certain conditions may serve as our most reliable geological thermometers, provided enough thermodynamic data of the minerals are known. The general principles underlying such thermometers are simple. (Fe,Zn)S mix-crystals formed from sphalerite and iron sulfide are common in ore deposits. In order to get information about the temperatures pertaining during the formation of such mix-crystals, the FeS-ZnS equilibrium diagram was studied experimentally. All runs were made in closed, evacuated silica tubes. The relationship between ZnS (wurtzite-sphalerite) inversion temperature and mix-crystal composition has been established. When Fe replaces Zn in the ZnS lattice, the metal-sulfur distance increases, suggesting an increase in the ionic character of the mix-crystal bonds. At relatively high temperatures equilibrium conditions were obtained by both mixing and unmixing. Exceedingly sluggish reactions below 400° C made it necessary to calculate the solvus curve below this temperature. Calculations, partially checked by experimentation, show that the influence of pressure on the FeS solubility in ZnS is relatively small. FeS activity decreases very little from stoichiometric FeS to FeS, but drops sharply when S is added beyond the amount indicated by the FeS formula. Small amounts of Mn and Cd have no measurable influence on the solubility of FeS in ZnS. Thus the variation in (Fe,Zn) S mix-crystal composition, as a function of temperature and pressure, is known. Provided sufficient iron sulfide was present, the mix-crystal composition reflects the temperature-pressure conditions existing during

ore deposition. The temperature of ore formation in many ore bodies has now been determined from the composition of (Fe,Zn)S type mix-crystals.

SULFUR ISOTOPES AND THE ORIGIN OF ORE-FORMING FLUIDS

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The sulfur isotope abundances in hydrothermal minerals vary over a considerable range although the sulfur in meteorites is constant. Sulfides from deep-seated mafic rocks have the sulfur isotope composition of meteorites. Sedimentary sulfide has a high S32/S34 ratio whereas sedimentary sulfate has a low ratio. Many hydrothermal sulfide deposits have either a high or low ratio of S32/S34 indicating that they were derived from a volume element of the crust instead of the mantle.

The isotopic ratio relative to meteoritic sulfur and the range of ratios within a deposit help define the source environment. Some information about the area pattern and time relations within a given deposit may be obtained by measuring samples with close geological control. The temperature or rate of deposition does not cause first order variations in the sulfur isotope ratios.

IGNEOUS ACTIVITY AND RELATED ORE DEPOSITION IN PERU, SOUTH AMERICA

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Petrologic studies of igneous rocks in the "Sierra" region of Central and Southern Peru have revealed a consistent pattern between extrusive activity, differentiation and intrusion of igneous masses and the related oxide and sulphide mineralization.

Two principal phases of Tertiary igneous activity are represented: an early period of extensive volcanic activity; and a later period of relatively quiet differentiation and intrusion which continued through the period of sulphide mineralization and was interrupted by local explosive volcanic activity. Differentiates of the second period are represented by plutons ranging in size from batholith proportions, irregular and mushroom-shaped stocks, to small dikes, and in composition from diorite and quartz-diorite, granodiorite, quartz-monzonite to alkali-rich quartz-monzonites and monzonites with accompanying textural and mineralogical changes. Mineralization geographically related to these intrusives is generally as magnetite-rich masses in contact areas of the early basic differentiates, as barren pyrite masses related to the intermediates, and as complex ore mineral deposition associated with the later acidic fractions. Post-ore alkali-rich, quartz-poor dikes cut the sulphide orebodies.

Ore-bearing fluid appears to have escaped from the differentiating magma following a trend of silica concentration and its escape was seemingly coincident with a sharp break in this compositional trend—a decrease in silica and lime in the post-ore intrusives.

The process of extrusion, differentiation and mineralization began in earliest Tertiary, extended through Pliocene and feebly continues today. The extensive volcanic activity appears to have been concentrated in early Tertiary with the igneous intrusions and formation of ore deposits confined to Miocene and Pliocene.

QUALITY CONTROL IN THE SELECTIVE MINING OF MAGNESITE AT GABBS, NEVADA

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A source of magnesium during the last war when nearly a million tons of the material were treated for the extraction of the metal, the magnesite deposits at Gabbs in west-central Nevada are presently being mined and processed into a variety of granular refractory products for use as furnace linings in the steel industry.

The magnesite occurs as the crystalline carbonate in layers or beds aggregating several hundred feet in thickness within a thick sequence of gently dipping Upper Triassic dolomite. The deposits are thought of as resulting from sedimentary and diagenetic processes, the source of the magnesia possibly being disintegrating dolomite. This material, washed into a shallow closed basin rich in sulphates, would precipitate lime as gypsum with subsequent deposition of hydrous magnesium carbonates. These would be dehydrated as the pressure of sedimentary loading increased. Later structural deformation and igneous activity, including the intrusion of a mass of quartz diorite, may have produced some of the hydrothermal effects observed. There is a remnant of a gypsum deposit in Upper Triassic dolomite within three miles of the magnesite. Dolomitization of the magnesite has occurred along open zones of stress or deformation.

Mining is by standard open pit methods using wagon drills, twenty-ton trucks and a 2½-yard shovel. Exploration is done by diamond drilling after preliminary geologic mapping.

The purity of the magnesite has been variously affected by the deposit's complex geologic history, making quality control a problem. The wagon drill hole cuttings are analyzed for lime and silica. A chemical contour map is prepared, showing the lime and silica distribution separately. After a bench is blasted, the ore grade boundaries, combining the lime and silica specifications, are staked out. Selective removal of the various grades of material and at the same time some blending is thus possible.

FLUORSPAR DEPOSITS IN COAHUILA, MEXICO

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Economic deposits of fluorspar are abundant and widespread in certain mountainous areas in the State of Coahuila, Mexico. In a broad or general sense the deposits can be grouped into two large districts, a *Northern* and a *Southern*, with the dividing line (27° N Lat.) passing through the town of Cuatro Cienegas. For a detailed study, however, it is more convenient to group the deposits into at least five districts, namely: San Vicente-Mariscal; Del Carmen-Pico Etereo; El Tule; Encantada-Buenavista; and San Marcos-Paila-Australia.

All the fluorspar occurs in Cretaceous (Comanche) sedimentary rocks; most of the ore is found in limestone formations lithologically similar and equivalent in age to the Georgetown-Edwards of the Texas section (equivalent in part to the Upper and Middle Albian of the Standard Section and to the Cuesta del Cura and Aurora formations of northern Mexico). Various stratigraphic, structural, and geomorphic phenomena influenced the fluoritization and localization of the de-

posits. It is likely that all the fluorspar is genetically related to rhyolitic intrusive rocks, but such rocks are not always exposed in the immediate vicinity.

The fluorspar is epigenetic, hydrothermal (probably both epithermal and mesothermal) and, at one place or another, is the result of one or more of the following processes: contact metamorphism; replacement; replacement-filling; and cavity filling. Among the types of deposits found are: fissure veins, thin mantos, breccia chimneys, collapse-breccia deposits in sinks; solution cavity filling; small, irregular-shaped bodies along erosional unconformities; small pods in contact aureoles; and xenoliths in intrusive rhyolite.

THE SOLUBILITY OF SOLIDS IN GASES

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The concept of a solid being dissolved by a gas appears paradoxical, but the reality of this solubility process has been demonstrated many times by many workers. From Dalton's law of partial pressures it would be expected that the amount of solid in the gas would be insignificant. The increase in vapor pressure of the solid by pressure, called the Poynting effect, does not change the order of magnitude. But the actual amounts of solid in the gas are always much larger than that predicted from simple theory, an effect to be ascribed to a true solubility of the solid in the gas. The order of magnitude of this solubility ranges from three times that expected from the vapor pressure in the system air-ice at −35° and 200 atmospheres pressure, 1481 times in the system air-solid carbon dioxide at −150° and 200 atmospheres, to more than a million times in the system water-sodium chloride or a million million times in the system water-quartz. A critical review of some of the older work is presented, as well as unpublished results from the Geophysical Laboratory on salts and oxides, and on the influence of mixed gases such as water and carbon dioxide.

THE QUEBEC–LABRADOR ORE AND ITS RELATIONSHIP TO THE SOKOMAN FORMATION

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The Quebec-Labrador iron field, which straddles the provincial boundary north of the 55th parallel, ranks with the largest iron deposits in the world. Thirty of the known deposits lie within 150 square miles of territory extending northwest from Wishart Lake to Goodwood.

The ore, although variable in character, grade, and quality, has been mined by open pit methods during the past two years. Moderately selective mining is practiced at present.

The ores are classified into two groups: those which retain diagnostic protore features and those characterized by additions of secondary hydrated iron oxides.

Those which retain recognizable protore features may have been converted to ore simply by leaching of silica, magnesia, and carbonates, with little or no addition of iron.

The distribution, character, grade, and quality of both types of ore are closely controlled by structure and show marked variations in sympathy with the character of the protores from which they were derived.

A CRITICAL EVALUATION OF THE CLASSIFICATION OF ORE DEPOSITS OF MAGMATIC AFFILIATIONS

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The purpose of this paper is threefold:

1) to summarize in as concise a form as possible the relative geological and physical-chemical data.
2) to criticize the present systems of classifications.
3) to suggest the lines along which modifications of these classifications should be carried out.

The distribution of the elements in igneous rocks is considered in relation to the periodic table; a generalized form for the standard mineral paragenesis is proposed; data relative to the character of the ore fluid at the various stages in the formation of ore deposits are examined; and the roles of temperature and pressure in the formation of epigenetic ore bodies are evaluated.

The widely accepted view that the "so-called" epithermal, mesothermal, and hypothermal deposits were formed at progressively deeper depths and higher temperatures is challenged, and it is suggested that some of the confusion in the present systems of classification is due to the fact that high temperature, but relatively near surface deposits, do not readily fit into this system.

It is suggested that a more effective system of classification would give greater stress to: 1) the relative position of the ore minerals in the standard paragenesis; and 2) the observed association of the various metals to particular igneous rocks and the intimacy of this relationship.

It is concluded that there is a need for a more effective system of classification of ore deposits in general and those of magmatic affiliations in particular, based on all recognizable geological variations, and, as far as possible, free of any terminology or artificial divisions based on theoretical considerations.

DEUTERIC ALTERATION AND ITS POSSIBLE SIGNIFICANCE TO WALLROCK ALTERATION IN SOME ROCKS OF THE BOULDER BATHOLITH, MONTANA

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Many of the complex aplite-pegmatite bodies of the Boulder Batholith contain rock in which plagioclase is altered to kaolinite and biotite to hydromica and to rutile; more intense alteration resulted in the formation of sericite and of sanidine. Such alterations are related only to internal structural features of aplite-pegmatites. Most commonly the alterations comprise small, irregular, and vaguely outlined bodies of rock, usually spatially related to coarsened texture, to tourmaline, or to both. In some bodies, feldspar alteration forms zones on one or both borders of an aplite-pegmatite or is disposed along internal joints. Similar feldspar alteration occurs as thin discontinuous sheaths in quartz monzonite around some aplite-pegmatites.

The chemical and textural characteristics of these alterations are the same as those in most of the adjacent ore deposits. Alterations in aplite-pegmatites differ from those related to ore deposits in being less intense and in lacking added minerals.

The alterations in the aplite-pegmatites are structurally so situated as to require their formation during the crystallization period of the adjacent quartz monzonite. They are probably due to the outward seepage of the residual solutions. The

alteration may be a consequence of high water-vapor pressures resulting from entrapment of residual solutions in sealed volumes within the crystallizing aplite-pegmatite bodies. From this study, it is postulated that residual magmatic solutions are locally adequate to cause the wallrock alteration found in ore deposits.

ASSOCIATION OF RARE-EARTH METALS WITH ALKALIC ROCKS AT MOUNTAIN PASS, CALIFORNIA, AND OTHER LOCALITIES

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The association of rare-earth metals and other uncommon elements such as Th, Nb, Ta, Zr, Ba, and Sr with alkalic rocks has been recorded in many parts of the world. Carbonatites associated with alkalic rocks are particularly favorable for the concentration of some rare elements, and interest in these rocks as possible sources of rare metals has increased in recent years.

In the Mountain Pass district, California, rare-earth and thorium deposits discovered in 1949 are associated spatially and genetically with small intrusive bodies ranging in composition from shonkinite through augite syenite and leucosyenite to granite. The rare-earth minerals bastnaesite, parisite, monazite, allanite, and sahamalite occur in carbonatite composed chiefly of calcite and barite. Thorite and thorogummite with some rare-earth minerals occur in veins along shear zones cutting Precambrian gneiss and the alkalic igneous rocks.

Among other examples of this association is the Powderhorn district, Colorado, an area long known for the alkalic rock complex at Iron Hill. Since 1949 thorium, at least partly as thorite and thorogummite, has been found along shear zones in Precambrian granitic and metamorphic rocks, chiefly in parts of the district where dike rocks such as shonkinite and syenite also occur. In a reconnaissance of the thorium-bearing veins, several minerals containing rare earths of the cerium group were found in small quantities locally in bodies of carbonate rock near Iron Hill. The rare-earth minerals include bastnaesite, synchisite, cerite (?), and rare earth-bearing fluorapatite.

ECONOMIC GEOLOGY OF SALEM LIMESTONE IN THE INDIANA BUILDING STONE DISTRICT

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The Salem limestone crops out along the east, south, and west margins of the Illinois Basin, but is quarried extensively for building stone only in a narrow belt 40 miles long in south-central Indiana, where pure, even-grained, massive limestone that is composed of small fossils and fossil fragments constitutes most of the formation.

Economic considerations that determine quality of quarry sites include color and texture of the stone, amount of rock overburden, character of the upper rock surface, and the number and nature of joints, bedding planes, stylolites, and interbeds of rock unsuitable for fabrication into building stone. Of these factors, texture, bedding, stylolites, and homogeneity are not predictable by present geologic methods, but can be tested by coring. Color can be determined by coring and may also be foreseen in a general way by close study of probable groundwater level as shown by the altitudes of surface drainage lines in the region. Amount of rock over-burden is revealed by coring and also can be estimated from detailed geologic

mapping. The character of the upper rock surface may be forecast with some accuracy from detailed mapping and petrologic study of the shallowest beds.

Geology has been little used by the industry but will be needed in the search for new quarry sites, in solving quarrying and fabricating problems, and in the development of new products and by-products in a highly competitive industry.

LATE EOCENE METALLOGENETIC EPOCH IN THE BEARPAW MOUNTAINS, MONTANA

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A late Eocene metallogenetic epoch in the Bearpaw Mountains of northcentral Montana is represented by several kinds of sulfide-bearing deposits that are genetically and temporally related to a single magmatic episode among several in the complex development of the mountain range. In a composite stock in the west-central part of the mountains, this metallogenetic epoch is illustrated by four gradational varieties of deposits: (1) a disseminated sulfide deposit of some magnitude in which the sulfides make up at least 2 and up to 6 percent of a sericitized porphyritic potassic syenite member of the stock; (2) feldspar-rich pegmatites with biotite and calcite and up to 15 percent sulfides; (3) irregular biotite-rich veinlike deposits containing fresh feldspar and calcite and sulfides; and (4) calcite-rich veinlike deposits containing fresh feldspar, biotite, aegirite, sulfides, and rare-earth minerals. Elsewhere in the mountains the epoch is represented by sulfide-bearing dikes of syenite, carbonate-sulfide smoky quartz veins, and smoky quartz veins. In the syenite, extensive sericitic and cancrinitic alterations were completed before the deposition of equally extensive sulfides and calcite. Sericite and cancrinite, however, are absent in the feldspar-bearing pegmatites and veins, and hydrous minerals other than biotite are rare.

The mineral deposits of this metallogenetic epoch may very well represent a succession of continually changing fluids developed at this level of the crust as a result of the consolidation of the potassic syenite (here considered the "ore bringer"). The sulfur, carbon dioxide, and other fugitive constituents were indigenous ingredients of the irrupting magma and became more concentrated as precipitation of the stable constituents continued in the form of feldspar, pyroxene, etc. It seems an acceptable conclusion that late magmatic fluids became relatively rich in fugitive constituents and that these fluids became mobile, entered fractured areas, and formed mineral associations dependent on the composition of those fluids and on the temperature and pressure gradients. Some of these fluids are believed to have such extraordinary concentrations of sulfur and carbon dioxide that part of the mineral-forming process may be classed as sulfothermal and carbonothermal rather than hydrothermal.

NOTES ON SEQUENCE OF VEIN FORMATION IN THE NORTHERN PART OF THE BOULDER BATHOLITH, MONTANA

FORBES ROBERTSON,* D. M. PINCKNEY ** AND M. R. KLEPPER **

Quartz ± tourmaline ± pyrite ± molybdenite crystallized in a feldspar-stable environment as segregations in pegmatites and in an essentially feldspar-stable environment as veinlets in batholithic rocks. The same minerals ± base-metal sulfides crystallized in simple veins and complex vein zones in batholithic rocks in which feldspars are sericitized and argillized.

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Simple veins of quartz ± pyrite ± tourmaline ± base-metal sulfides enveloped by sericitized and argillized rock probably formed during a single local episode of fracturing and replacement. Complex vein zones, consisting of a few or many veins and gouge strands in altered rock and as much as several miles long and several hundred feet wide, probably formed during repeated episodes of fracturing and replacement.

Soil sampling and detailed examination of dumps indicate that a considerable portion of many veins and vein zones contain virtually no base metals. These observations suggest that the solutions that accomplished the alteration did not necessarily contain appreciable amounts of base metals. Furthermore, structure and distribution of base-metal ore bodies within veins and vein zones and paragenesis suggest that most of the lead and zinc was introduced after an early generation of quartz and pyrite ± tourmaline and prior to a generation of chalcopyrite, pyrite, and quartz. Not all generations are represented in most veins or even in most complex vein zones.

COMPOSITION OF FLUID INCLUSIONS

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Most discussions concerning ore transport and deposition depend on assumptions as to the composition of the ore-bearing fluid. Any factual evidence, however meager, as to the compositions of these fluids would be of great value in determining the mechanisms of transport and deposition.

Vein quartz generally contains large numbers of fluid-filled microscopic inclusions. The inclusions in crystals lining vugs presumably represent samples, trapped during the growth of the crystal, of the medium from which the quartz and all simultaneously crystallizing minerals were formed. In sheared gold quartz veins, the inclusions represent samples of fluids present in the vein during the "healing" of fractures in the quartz and hence possibly the very fluids from which the gold or late sulfides were deposited.

Methods have been developed whereby it is possible to extract the fluid from a large number of these inclusions (e.g., from one kilogram of quartz) and to analyze it chemically for certain constituents. The method consists of 1) mineralogical separation to obtain pure crushed quartz, 2) thorough electrolytic cleaning to remove surface adsorbed ions, 3) opening inclusions by ball milling in alumina mills or by decrepitation, and 4) collection of inclusion ions by electrodialysis and gas analysis methods.

Results presented show that the fluid inclusions in a number of samples contain a water solution rich in chlorides and carbonates of potassium and sodium with lesser amounts of other ions. Ratios between various ions are relatively reproducible and make the method useful on a variety of geological problems.

*THE OKA ALKALINE COMPLEX AND ASSOCIATED COLUMBIUM DEPOSITS**

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This paper describes the Oka alkaline rock complex and the associated columbium deposits of the Oka District, Two Mountains County, Quebec.

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The complex probably belongs to the Monteregian petrographical province and is characterized by enrichment in sodium, iron, titanium, phosphorus, columbium, and chorium. It is composed chiefly of carbonate rocks, okaite, rocks of the ijolite series, lamprophyre rocks, and biotite replacement rocks. A pronounced magnetic anomaly is caused by the high magnetite content of the complex. The country rocks are Precambrian and are altered in places at the contacts with the complex. Breccias and lamprophyre dykes are satellites.

The deposits are potential large-tonnage sources of columbium. Pyrochlore, the principal columbium mineral, occurs in disseminated replacement deposits in carbonate rocks. Betafite occurs in places in biotite replacements, and columbian perovskite occurs in altered okaite and altered ijolitic rocks. Seven mining companies are conducting extensive diamond drilling programs and several millions of tons of pyrochlore-bearing rock are indicated.

Problems of origin and the relationship of the complex to other alkaline rock complexes in Ontario and Quebec will be discussed.

GENETIC SIGNIFICANCES OF QUARTZ–MOLYBDENITE MINERALIZATION IN THE BUTTE DISTRICT, MONTANA

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Molybdenite is found in the Butte District in quartz-rich pegmatite core zones, in discontinuous quartz-rich pods, and in well-defined banded veinlets, all in the quartz monzonite. Some of the banded veinlets also cut the "quartz-porphyry" intrusive. Pyrite, chalcopyrite and rarely pyrrhotite are the only other sulfides in these assemblages. The copper and zinc sulphide veins cut and offset the molybdenite-bearing structures.

Often the molybdenite in the pegmatites is in contact with fresh feldspars, but some of the banded quartz-molybdenite veinlets are enveloped in typical Butte alteration zones of sericite and clay minerals. At any given zonal level in the Butte District, concentration and deposition of molybdenite thus began in the late pegmatite stage when feldspars were also crystallizing. Molybdenite continued to be deposited, as banded veinlets, from solutions that ultimately converted the feldspars to sericite and clay minerals. But there is no evidence for further molybdenite introduction once the East-West vein structures were formed and copper and zinc began to be deposited in them.

Thus, at Butte, the concentration of molybdenite involves processes that are transitional between late magmatic activity and the main hydrothermal inundation. This position suggests geochemical similarities, as well as contrasts, between Butte and other copper ore bodies such as La Colorada and certain of the "porphyry coppers."

GEOLOGY IN DEVELOPMENT AND MINING, SOUTHEAST MISSOURI LEAD BELT

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The use of geology in metal mining districts is considered in terms of four distinct phases, namely: (1) period of no organized geological program, (2) period of limited geological program, (3) period of research and underground mapping, and (4) period of applied geology. Mining history in the Southeast

Missouri Lead District is interpreted relative to the above classification. The present geological program is late in the third phase.

In addition to the discovery of new ore, mining geology contributes to a favorable mining cost by reducing development risks and by aiding in more economic extraction of ore. To reduce development risks, the geologist in the Southeast Missouri District evaluates each orebody on the basis of drill core study, knowledge of structural relationships, contour and isopach maps of stratigraphic units, and production history of the ore zone. Orebodies are rated on a mining probability scale of 1–5.

Periodic visits to operating stopes are useful in anticipating ore trends, thereby permitting adjustments in operating practice resulting in more complete extraction and less dilution of ore. Prospecting is used in conjunction with mining to expand the ore reserve available to operating stopes.

Ore potential of approximately 450 orebodies in widely different structural settings and stratigraphic zones is periodically evaluated and reduced to number of drill shifts remaining in each orebody. This provides a basis for anticipating exhaustion of individual orebodies, planning the type of development needed, and maintaining balance of mining in different areas.

GEOLOGICAL MAPPING BY LIGHT HELICOPTERS, N.W.T., CANADA

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In order to speed up the regional mapping of northern Canada, the Geological Survey in 1952 launched its first experimental helicopter survey in the barren grounds of the Northwest Territories, between Hudson Bay and Great Slave Lake. Operation Keewatin (1952) and its successors, Baker (1954) and Thelon (1955), have mapped 185,000 square miles, on the scale of eight miles to one inch, at an average cost of $2.67 per square mile. The centre of this area is 400 miles from the nearest railhead.

Each operation required 15–16 men, including five trained geologists; used two helicopters and one Norseman aircraft; and necessitated the preseason caching of about 120 tons of gasoline and provisions.

The helicopters were used almost exclusively for geological observation, and the Norseman was used to move base-camp within the operation area, and to bring in supplies from major caches.

Geological data were obtained from 5,000 landings, 10,000 low passes (below 50 feet), and innumerable high-level observations (above 50 feet).

Compared to conventional canoe-reconnaissance surveys, the helicopter method is economical in trained men and money, more flexible and independent of canoe routes, gives more uniform coverage, and is capable of covering the great areas involved quickly and without an unacceptable lowering of mapping standards.

SCIENTIFIC NOTES AND NEWS

GABOR DESSAU, after retiring in September 1953 from the Italian Government Service, has continued as "chargé de cours" of Mineral Deposits at the University of Naples, and has from its inception been in charge of the Uranium Prospecting Center (Centro Ricerche Minerali Radioattivi) of the ENI-AGIP group. In October 1955 he came to the "Technion" (Hebrew Institute of Technology) in Haifa as UNESCO expert for one year to advise on the setting up of a Geological Engineering and Mining Department.

MOSTYN G. GRANT, formerly in charge of exploration work in Butte, Montana, carried on by Coronado Copper and Zinc Co., a subsidiary of Cyprus Mines Corp., is now located in Tucson, Ariz.

FRANK CONROW, Butte, Montana, has been named geologist on the exploration staff of western operations, U. S. Smelting, Refining and Mining Co., with headquarters in Salt Lake City, Utah.

W. C. ACKERMAN, formerly resident geologist with the Colorado Fuel and Iron Corp., Sunrise, Wyo., has now joined the minerals beneficiation division of Battelle Memorial Institute, Columbus, Ohio.

LEO MILLER, geologist with the AEC Operations Office, Grand Junction, Colo., has resigned to join the Pick Uranium Co. as director of exploration and geology.

EDWARD L. CLARK, state geologist for Missouri, has joined Four Corner Uranium Corp. as vice-president in charge of development and exploration.

ALBERTO J. TERRONES, assistant chief geologist, exploration, Cerro de Pasco Corp., has left Lima, Peru, and returned to his home in Mexico.

JOHN R. RAND, resident geologist for Copper Range Co. and White Pine Copper Co., has resigned to enter private consulting practice with an office at 482½ Congress Street, Portland, Maine.

CHARLES H. BOWEN has been appointed geologist for the U. S. Atomic Energy Commission, Grand Junction, Colo.

WAYNE R. ZWICKEY is now geologist for the New Jersey Zinc Co., Platteville, Wis.

MAX KREY and E. J. SCHUH, geological consultants, have opened an office in the Commerce Building, 127 N. 4th Street, Grand Junction, Colo.

RICHARD M. FOOSE, formerly of Franklin and Marshall College, Lancaster, Pa., is now with the geology department of Stanford University, Stanford, Calif.

DAVID L. MOORE, of Rosario Exploration Co., Grand Junction, Colo., has joined the minerals beneficiation division of the American Metal Co., Ltd., in New York.

WILLIAM H. SWAYNE is chief geologist for South America for the Anaconda Co. with headquarters at the Chile Exploration Co. in Chiquicamata.

ARTHUR BEVAN, principal geologist of the Illinois State Geological Survey since 1947, has retired. Mr. Bevan will resume field studies in the Appalachians of west-central Virginia. From 1929 to 1947 Mr. Bevan was state geologist of Virginia

HUGH DOUGLAS is now with American Overseas Petroleum Ltd., New York, as geologist. Mr. Douglas was formerly with Texas Gulf Sulphur Co., New York.

CHARLES G. EVENSEN is associate professor, geology department, Texas Western College, El Paso. Mr. Evensen was formerly with the U. S. Atomic Energy Commission, Kayenta, Ariz., and at Grand Junction, Colo.

THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS, ROCKY MOUNTAIN SECTION, will hold its sixth Annual Meeting in Denver, Colo., from February 27 to 29, 1956.

WILLIAM A. BREWER is assistant geologist, Chile Exploration Co., Chuquicamata, Chile. Mr. Brewer was graduated from the University of California last June with an M.A. degree in geology.

ROBERT M. CHAPMAN, of the U. S. Geological Survey, College, Alaska, has been transferred to the Navy Oil Unit, USGS, Washington, D. C.

ALLAN E. JONES has been named deputy manager of the AEC's Grand Junction Operations Office, succeeding EDWIN H. CRABTREE, who resigned to become director of the Colorado School of Mines Research Foundation. For the past three years, Mr. Jones has been on assignment in Johannesburg, South Africa, for the AEC raw materials program.

THOMAS L. KESLER, chief geologist, Foote Mineral Co., has returned from a third of a series of trips covering development in the lithium-ore districts in Canada by the company.

GORDON DEAN, associated with Lehman Brothers; JOSEPH H. HIRSHHORN, metal mining executive; and PHILIP D. WILSON, consulting mining engineer and geologist, have been elected directors of Callahan Zinc-Lead Co.

RICHARD L. SCHUMACHER, former geologist for New Jersey Zinc Co., has joined Manu-Mine Research and Development Co., Reading, Pa.

PLAINE L. WISEMAN is now located in Cananaral, Chile, as junior geologist for the Andes Copper Mining Co., a subsidiary of the Anaconda Co.

EARL INGERSON, chief of the Geochemistry and Petrology Branch, U. S. Geological Survey, was the eighth recipient of the Arthur L. Day Medal of the Geological Society of America at the 68th annual meeting of the Society in New Orleans, November 7, 1955, "in recognition of his outstanding distinction in the application of physics and chemistry to the solution of geological problems."

J. J. BRUMMER has joined the staff of Kennco Explorations (Canada), Ltd., with headquarters in Quebec City. He was formerly chief geologist for Rhodesian Selection Trust (Services) Ltd. and Mufulira Copper Mines, Ltd., Northern Rhodesia.

CHARLES E. MELBYE and STUART S. MERWIN are no longer partners in Minerals Exploration Research Corp. and are now geological and geophysical consultants with offices in the First National Bank Bldg., Golden, Colo.

C. PHILIP JENNEY, formerly assistant manager, Exploration Dept., American Metal Co., Ltd., New York, has returned to Toronto and will open a consulting office at 372 Lakeshore Highway West, Oakville, Ontario, after the first of the year.

THE U. S. CIVIL SERVICE COMMISSION has announced a new examination for Geologist for filling positions paying from $5,440 to $8,990 a year in Federal agencies in Washington, D. C., and throughout the United States. A few positions in the Territories and possessions of the United States may also be filled. To qualify,

applicants must have had appropriate college study and, in addition, professional experience in geology. Part of the required experience must have been in one of the specialized fields of geology. No written test is required. Applications for these examinations will be accepted until further notice and must be filed with the Executive Secretary, Board of U. S. Civil Service Examiners, Geological Survey, Department of the Interior, Washington 25, D. C. Further information may be obtained from many post offices throughout the country or from the U. S. Civil Service Commission, Washington 24, D. C.

SIR EDWARD C. BULLARD, director of the National Physical Laboratories, Teddington, England, delivered a public lecture at M.I.T. on the "Materials of the Interior of the Earth" in November of last year.

RICHARD R. DOELL and JOHN W. WINCHESTER have been appointed assistant professors in the department of geology and geophysics at the Massachusetts Institute of Technology. Dr. Doell, who is now Lecturer in Geophysics at the University of Toronto and who received his Ph.D. in geophysics from the University of California (Berkeley), will lecture and direct research in seismology and geomagnetism at M.I.T. Dr. Winchester, now on a Fulbright Fellowship in Amsterdam, received his Ph.D. in physical chemistry from M.I.T., and will instruct and conduct research in nuclear geochemistry.

The Department of Geology and Geophysics of the Massachusetts Institute of Technology and the Geophysical Laboratory of the Carnegie Institution of Washington are cooperating in the award of pre-doctoral fellowships in theoretical and experimental geology. The awards are to be known as the VANNEVAR BUSH FELLOWSHIPS IN EARTH SCIENCES, in honor of Dr. Bush who long served as Professor, and later as Dean and Vice President at M.I.T. and more recently as President of the Carnegie Institution of Washington. Candidates for an award must have advanced training in mathematics, physics and chemistry, and a broad knowledge of the earth sciences. Recipients will have unusually favorable opportunities to do thesis work on challenging new problems in the most active and rapidly moving fields of earth science. Applicants for the award must have completed all M.I.T. requirements for the Ph.D. degree except thesis, and will be registered as full-time doctoral candidates at M.I.T. during that part of their graduate study in which they are in residence at the Geophysical Laboratory. While at the Geophysical Laboratory, the Fellow will receive $200 per month (plus appropriate tuition) for the first 12 months and $225 per month (plus tuition) for the duration of the fellowship. Upon returning to M.I.T., the recipient will continue to receive the same monthly stipend as last received from the Geophysical Laboratory, in addition to tuition.

Those interested should write to the Chairman, Department of Geology and Geophysics, 24-302 M.I.T., Cambridge 39, Massachusetts.

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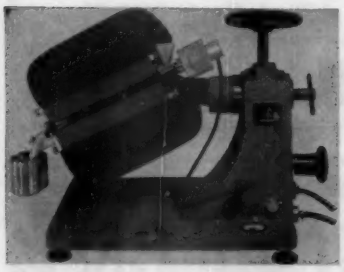

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